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VOLUME 2
NUMBER 2
FEBRUARY
1963

A monthly publication of the Optical Society of America

John N. Howard, Editor
James G. Baker, Feature Editor
Patricia R. Wakeling, Managing Editor

COVER: Three (of five) solar telescopes designed for simultaneous use on a common photoelectrically guided mounting at the Sacramento Peak Observatory of the Air Force Cambridge Research Laboratories (Sunspot, New Mexico). The main 16-inch (40.6-cm) coronagraph on top forms a solar image via a coudè mirror system on a large fixed spectrograph, spectroheliograph, and other accessories in an observing laboratory.

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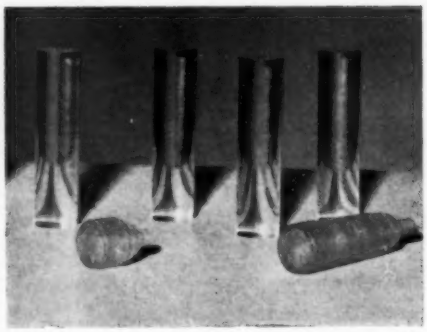

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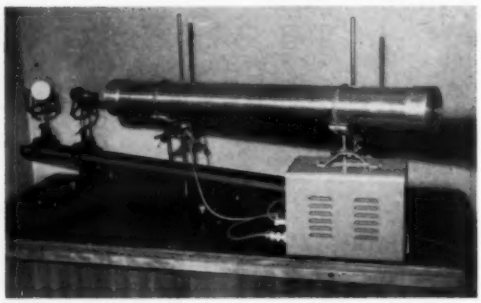

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OPTICAL MASERS

published December 1962

In the APPLIED OPTICS Supplement on Optical Masers, published December 1962, concepts basic to the understanding of optical masers are discussed in a 15,000-word paper by **O. S. Heavens,** Royal Holloway College, which in addition reviews the progress of this new field. Work on solid-state systems is summarized, and applications in the areas of fundamental experiments, communications, instrumentation, and surgery discussed. Gas systems are dealt with in a comprehensive review by **W. R. Bennett, Jr.,** Yale, comprising some 20,000 words. Selected papers from the publications of the Optical Society of America and of other societies are reprinted in this comprehensive volume, and suggestions for further reading are given. The editorial to OPTICAL MASERS is written by **Charles H. Townes,** MIT.

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Planetary Telescopes

James G. Baker

A review is made of present possibilities in the design of large refracting telescope objectives intended for visual or detector-aided studies of the planets from ground-based observatories. The great progress in the technology of optical glass achieved during the past several decades makes it worthwhile now for one to re-examine the question of whether the performance of any large refractor made in the future can be improved. On the whole the answer is affirmative but with reservations as to the importance of such an accomplishment in modern astronomy. A comprehensive discussion is given of the optical and environmental problems encountered, and several examples are given to demonstrate the degree of improvement to be expected from both semiapochromatic and fully apochromatic objectives.*

Introduction

In the history of planetary astronomy various efforts have been made to construct refracting telescopes of supreme quality that would enable a keen-eyed observer to work down to the theoretical limit of what is scientifically possible in accordance with the diffraction behavior of light, the low contrast of planetary surface detail, and the limitations imposed by atmospheric seeing. In retrospect, however, every large refracting telescope that has ever been built suffers from one or more residual defects of appreciable importance. It is a fair statement to make that no completely satisfactory large refracting telescope exists even today, and this observation is true even without including consideration of the equally vital matter of location.

For many decades telescopes used for astrophysical researches have nearly always been reflectors. Indeed, the limitations of the refractor in terms of spectral coverage, light gathering power, and even of cost have persuaded most astrophysicists to use only the reflecting telescope, and, for physical studies of the planets, usually the Cassegrainian form of reflector. The long-established trend toward reflectors for nearly all astrophysical and astronomical purposes has gone so far that a recent book broadly entitled *Telescopes*[2] fails to include any technical discussion of the large refractor at all. Such an omission is a pity, for the refractor has many desirable properties and in improved forms should continue to serve astronomy.[3]

In the present paper the title "Planetary Telescopes" is used in a classical sense, namely, to designate refractors of substantial focal length and aperture with objective lenses designed to yield the best possible image quality for visual or detector-aided studies of the surface features of the planets.

Optical Glass

During the past twenty-five years there has been a drastic improvement in the technology of optical glass brought about by intensive demands shortly before and during World War II, in the postwar years by the expanding requirements of international competition, and lately, by the stringent needs of the space sciences. In addition to the continuing development of dozens of new types of optical glass a near revolution has occurred in the manufacture of glass itself through the large scale use of platinum-shielded crucibles* and through an ever-increasing understanding of the physics and chemistry of glass. As a result many of the older types of glass, which had been troublesome to produce because of compromises that had to be made between the temperature required for good workability and that required to prevent reactions of the molten glass with the walls of the container, have now become among the easiest to produce. Platinum-melted dense barium crown glass can be obtained essentially free of bubbles and more nearly free of iron coloration than ever before. The high cost of platinum, however, imposes an obvious limit on the size of melt.

The author is at the Harvard College Observatory.

Received 10 November 1962.

This work was carried out as a private contribution of the author in form of a supplement to supported work under a NASA subcontract with Harvard University for JPL.[1]

* The author would like to acknowledge the opportunity of seeing, prior to publication in the June issue, the paper by Max Herzberger and Nancy R. McClure entitled "The Design of Superachromats".

* Michael Faraday used platinum trays and stirring rods in experiments on glass-making as early as 1825.

Excellent glass of a large variety of types in all reasonable shapes and sizes for normal use in optical instruments is available commercially from a number of distinguished companies with many years of experience.* However, only a very few firms have made disks as large as 80 cm in diameter in any quantity. In particular, Jenaer Glaswerk Schott & Gen. of Mainz, West Germany, has been producing "Objective Grade" disks of a variety of glass types for many years. These disks are guaranteed to be of a quality fully satisfactory for the most critical use and therefore must attract the attention of anyone interested in planetary telescopes. Very likely Alvan Clark never enjoyed the privilege of working glass disks quite so fine in over-all quality as the modern Schott disks of objective grade. Even though the homogeneity still may not be quite good enough for the very largest objectives, an optician would not have to be an Alvan Clark to complete the figuring by aspheric "touching-up." One would have to do some figuring anyway after coming within a fringe or two of each of the prescribed surfaces.

Not only is optical glass of objective grade free of even very fine striae as determined by schlieren testing, but it is more nearly free of bubbles and coloration than ever before. White light transmission has also been maximized, and the homogeneity of refractive index is guaranteed to plus or minus 0.000005 or better.[4] Annealing can be held to 5 mμ/cm or better, and residual stress can be maintained in radial symmetry with respect to the center of the disk. Equally good disks can be obtained domestically for a few types of optical glass, or in large quantities when the demand exists, or for small disks, but often without sufficient laboratory proof of excellence.† It is to be hoped that all makers of optical glass will provide glass of objective grade when required, and that suitable guarantees in the form of precise laboratory measurements will accompany delivery of the glass. The older designation of "telescope blanks" conveys assurances of excellence but lacks quantitative proof from the laboratory.

Disks of objective grade have been produced even in very large diameters. The largest disk known to the author and thought to be of objective grade is of BK-7 type. The disk is approximately 2.3 m in diameter and 18 cm thick, cast originally with the expectation that it might be used for the Isaac Newton telescope. BK-7 disks for schlieren use intended to approximate or even to be of objective grade can now be ordered in diameters up to 3.8 m. More reasonably, one can count on obtaining glass of objective grade up to 1 m in diameter for a number of crown glasses and for many of the usual flint glasses. If cost can be neglected, the skill and knowledge exist to carry through the necessary experimentation for even larger disks and for more types of glass.

It should be pointed out that, even if some glass types are not available in large diameters in objective grade, a close approximation may be obtained in semiobjective grade or plattenglas. The first deficiency to appear is likely to be fine striation, but homogeneity and annealing may be fully as good as in objective grade. One must decide in advance whether the given application allows some small percentage of scattered light. For example, photographic objectives for all but the most exacting uses will permit some scattered light in view of the fact that the turbidity of the emulsion is worse by far. In astronomy, astrographic and astrometric wide-field photographic telescopes will suffer little, if at all, from a small percentage of scattered light.

Jenaer Glaswerk Schott & Gen. has kindly provided the author with a compilation of data for 227 glass types with respect to the maximum volume and maximum thickness available in both objective grade and plattenglas, either as produced or estimated. Table I contains selections from these data for glass types available in objective grade in volume of 20 liters or more. The material is published here with the kind permission of the company.

A lens blank in the form of a disk with plane-parallel faces will have approximately a 1 m diam for a volume of 60 liters for a ratio of thickness to diameter of 1:13. In Table I there are half a dozen glass types among the crowns that might be used as the positive element of an objective lens as large as the Yerkes refractor. The only matching flint glass for the negative element seems limited provisionally to 40 liters in objective grade or to the requisite 60 liters in plattenglas. On another occasion, however, in a separate inquiry the author has been advised that F-2 can be made available essentially in objective grade to a maximum volume of 75 liters. (See Table II below.)

It is probable that the optical glass available to Alvan

---

* a. Bausch & Lomb, Inc., Rochester 2, New York. Optical Glass Catalog.

b. Chance-Pilkington Optical Works, Pilkington Brothers Limited, St. Asaph, Flintshire, Great Britain. Optical Glass Catalog.

c. Corning Glass Works, Corning, New York. Optical Glass Catalog.

d. Eastman Kodak Company, Rochester, New York. Properties of Kodak Rare Element Glasses.

e. Hayward Scientific Glass Corporation, 217 Magnolia Avenue, Whittier, California. Properties of Precision Optical Glasses in stock or regularly produced. Catalog HG-361

f. Jenaer Glaswerk Schott & Gen., Mainz, West Germany. Optical Glass Catalog, 350 E and supplementary lists.

g. Nippon Kogaku Glass Company, Tokyo, Japan. Optical Glass Catalog.

h. Parra-Mantois & Co., 11 Chemin de Ronde, Le Vesinet, France. Optical Glass Catalog.

† Similarly, equally good glass is available from other large glass companies. Chance-Pilkington, for example, guarantees disks up to 30 cm diam to be of objective grade and performs interferometric examination of larger disks.

Table I. Maximum Volume List (as of April 1962)

Glass type[a]	Objective grade Volume (liters)	Objective grade Maximum thickness (mm)	Plattenglas Volume (liters)	Plattenglas Maximum thickness (mm)
PK-2	60	150	100	155
PK-3	(50)	(120)	(75)	(140)
BK-1	60	130	100	160
BK-6	(60)	(130)	(100)	(160)
BK-7	100	160	150:	200:
BK-8	(75)	(140)	(100)	(160)
BK-12	(50)	(120)	(75)	(140)
BK-13	(50)	(120)	(75)	(140)
BaLK-3[a]	(25)	(100)	(40)	(110)
K-3[b]	(30)	(95)	(40)	(110)
K-5	60	130	75	150
K-7	(30)	(95)	(40)	(110)
ZK-1	(20)	(80)	(30)	(100)
ZK-2	(25)	(90)	(40)	(105)
BaK-1	(40)	(100)	(50)	(110)
BaK-2	(40)	(100)	(50)	(110)
BaK-4	50	110	60	125
BaK-6	(20)	(80)	(30)	(90)
SK-1	(25)	(85)	(40)	(100)
SK-2	25	85	(40)	(100)
SK-3	(25)	(90)	(40)	(105)
SK-4	(25)	(90)	(40)	(105)
SK-6	25	85	40	105
SK-7	(25)	85	40	105
SK-8	(25)	85	40	105
SK-9	(25)	85	40	105
SK-10	(30)	90	50	110
SK-14 EBA[c]	20	80	25	90
SK-15	40	90	50	110
SK-15 EBA	(20)	80	25	90
SK-16 EBA	20	80	25	95
SK-18	(20)	80	25	90
SK-19	(20)	80	25	90
SSK-1	(30)	90	(40)	110
SSK-2	(25)	90	(30)	100
SSK-3	(20)	80	(25)	95
SSK-4	(25)	90	(30)	100
SSK-5 EBA	20	80	25	90
BaF-1	(30)	95	(40)	105
BaF-2	(30)	95	(40)	105
BaF-3	(30)	95	(40)	105
BaF-4	40	110	(50)	(120)
BaF-5	(30)	95	(40)	(105)
BaF-6	(30)	95	(40)	(105)
BaF-7	(30)	95	(40)	(105)
BaF-8	(25)	90	(30)	(100)
BaF-9	(25)	90	(30)	100
LF-1	(25)	90	(40)	105
LF-2	(25)	90	(40)	105
LF-3	(25)	90	(40)	105
LF-4	(25)	90	(40)	105
LF-5	40	105	50	120
LF-6	(25)	90	(40)	105
LF-7	(20)	80	(30)	90
F-1	(30)	95	(40)	110
F-2	40	105	60	130
F-3	(25)	90	(30)	100
F-4	(25)	90	(30)	100
F-5	(20)	85	(25)	95
F-6	(30)	95	(40)	110
F-7	30	95	(40)	110
F-8	(25)	90	(30)	100
F-9	30	95	(40)	110
F-10	(30)	95	(40)	110
F-12	(30)	95	(40)	110
F-13	(30)	95	(40)	110
F-14	(20)	85	(25)	95
F-15	20	85	(25)	95
SF-1	30	100	40	115
SF-1 FA[d]	20	90	25	110
SF-2	40	100	50	115
SF-3	30	95	(40)	115
SF-3 FA	20	90	25	110
SF-4	30	90	(40)	110
SF-4 FA	20	80	25	100
SF-5	40	110	50	125
SF-6	30	95	40	115
SF-6 FA	(20)	(90)	25	110
SF-7	(30)	95	(40)	115
SF-8	25	90	30	100
SF-9	25	90	30	100
SF-10	(30)	95	(40)	110
SF-10 FA	(20)	90	(25)	100
SF-12	(25)	90	(30)	100
SF-15	25	90	30	100
SF-16	(30)	90	(40)	110
SF-17	(30)	90	(40)	110
SF-18	(30)	90	(40)	110
SF-19	(25)	85	(30)	100
KzF-1	(20)	85	(30)	95
KzF-2	30	100	50	130
KzF-3	(20)	85	(30)	95
LaK-1	(20)	(90)	(25)	(100)
LaK-2	(20)	(90)	(25)	(100)
LaK-3	20	90	25	100
LaK-5	(20)	90	(25)	100
LaK-6	20	90	25	100
LaK-7	(20)	90	(25)	100
SFS-7	(20)	90	(25)	100

[a] Unfavorable bubble quality.

[b] With bubbles.

[c] The designation EBA in translation means much reduced bubble content. SK and SSK glasses not having the EBA designation do have numerous bubbles.

[d] The designation FA means with reduced coloration.

Clark corresponded on the average more nearly to plattenglas than to glass of objective grade.[6] Indeed, the Lick 91-cm objective shows noticeable striation in a Foucault test on a bright star. The crown element of the Lick refractor also shows considerable deterioration of the front surface to which glass types such as PK-2, BK-7, and BK-8 are not particularly subject.

It is noticeable to the author on perusal of Table I that some of the types now available in large volume in objective grade have received special attention in the past because of the design and development of large photographic systems. The author also feels that the tabulations in Table I are conservative on the whole and can be improved in many cases, given sufficient time and budgetary backing. For example, special research and development are now being carried out on the production of large disks of SK-2, SK-4, SK-5, SK-6, SK-14, SK-15, SK-16, and SK-20, all in EBA quality. SK-20 EBA, though not given in Table I, previously had been available in objective grade as of April 1962, only in a maximum volume of 2.5 liters. In the brief interim of six months SK-20 EBA has now been produced in a volume of 40 liters, and the same is likely to prove true in the near future for the other SK types mentioned immediately above. SK-2 has already been used in large astrographic lenses. SK-14 has been used extensively, though not in full objective grade, for the central aspheric element in the trio of correcting plates used in the optical system for the satellite tracking cameras of the Smithsonian Astrophysical Observatory. SK-5 EBA is also very promising for use in special photographic systems.

Thus, one might conclude that refracting telescopes can be made at the present time as large as or larger than the 102-cm Yerkes objective under the current conditions of intensive research support by interested governments. Limitations on transmission, often referred to in textbooks as a prime reason why larger refractors are impractical, are not quite so severe now that purer chemicals are being used, if needed. Flexure remains a serious factor, but one must note that engineering attention given the problem in no way can compare to that given the much more difficult task of mounting large astronomical mirrors.* The lens elements of the Lick 91-cm refractor are not only very thin for their diameter but are mounted in a 3-point kinematic fashion, the purpose of which is largely defeated by the flexibility of the elements. Flexure was a matter of concern, nevertheless, and the final testing and associated figuring took place with the optical axis directed to a zenith distance of approximately 37 deg.† With careful engineering it is likely that objectives somewhat larger than the Yerkes 102 cm could be successfully figured and mounted before the limitations of transmission and flexure become decisive. A far more serious stumbling block, however, to any proposal to build a refractor as large as or larger than either the Lick or Yerkes instrument is the fact that the color curve, or relationship of focus to wavelength, must be markedly improved if such large objectives are to be worthwhile.

Apart from the manifold difficulties of procuring glass disks of adequate quality,[7] the older workers also encountered this very serious limitation in satisfactory color correction. The largest refractors of standard crown and flint combinations have a dismaying color error to such a magnitude that one wonders why the astronomers of the period were bold enough to proceed with the construction of such instruments.[8] The "secondary spectrum" left over after the usual condition of achromatism has been met is not a small effect. The violet and deep red wavelengths for the Yerkes refractor focus many millimeters farther from the objective than the yellow-green "minimum focus." Certainly the problem received the closest attention from mathematicians and practical workers alike even as far back as Hamilton's and Fraunhofer's time. The defect lies more in the lack of availability of suitable glass types than in any lack of understanding, and this is largely true even today. Objectives with three or more elements are mathematically amenable* to superior color correction. The usual result, however, is that the internal dioptric powers so derived are very large in terms of the net power of the system. As a practical matter one must be very careful that the large thermal changes and flexure difficulties encountered in a multiple-element system of considerable diameter do not wipe out the gains achieved from improving the color correction.†

The presence of secondary spectrum is related mathematically to the lack of precise matching along the spectrum of the dispersive powers of the two or more glass types used in a compound objective to produce ordinary achromatism. In a doublet objective where only two types of glass are involved, full correction can only be achieved by selection of and indeed the existence of two matching types. In an objective with three or more elements selection of glass types remains important in order to keep the internal optical powers to a minimum, but in principle an exact solution can be achieved by the solution of corresponding simultaneous equations. In practice, the lack of adequate glass types remains the dominant difficulty.

In producing ordinary achromatism one speaks of

* See ref. 2, chaps. 1–3.
† See ref. 6, p. 59.

* Note particularly the Herzberger Superachromats.
† See ref. 8, pp. 36–40.

combining two colors of the spectrum,* such as the F and C Fraunhofer lines at 4861 and 6563 Å, respectively, or any other two colors intended to be parfocal with one another.[10] The designer has the freedom to place the minimum of the curve of focal position against wavelength at any place in the spectrum required by the problem at hand. In general this minimum will be chosen for representative rays of the aperture, which because of diffraction and for normal objectives can be taken about at the 0.7 zone of the pupil. A visual objective will have the minimum located approximately at the region of maximum sensitivity of the eye, namely, about 5550 Å. Many experienced workers in the field, however, have placed the minimum more toward the yellow or even orange-yellow region of the spectrum,[11] a circumstance that might seem to favor telescopes used particularly for studies of Mars. In any case the region of the spectrum lying within the Rayleigh diffraction limit for the largest objectives is quite small and amounts only to a few hundred angstroms, more or less.† In spite of the fact that the color curve of the eye favors the narrow minimum focus region and thus introduces a kind of filtering action, the resolution suffers, and the contrast rendition on surface objects especially is much reduced. For planetary work the inherent contrast is already low even when the seeing is excellent. An observer is thus appreciably handicapped by the presence of the secondary spectrum.

The Yerkes 102-cm refractor and the Lick 91-cm refractor both are afflicted to the fullest extent with secondary spectrum and in addition have other residual troubles of scattered light, flexure, and weathered surfaces that increase the difficulties of observation. The exposed front surface of the 91-cm refractor in particular contains a myriad of sleeks produced by atmospheric attack over the decades, and these sleeks produce a noticeable amount of scattered light around the apparent disk of a planet. However, the partial deterioration of the 91-cm objective is not typical, and many other old telescopes are in much better condition. The Harvard 38-cm refractor, for example, shows an almost clear front surface after 115 years of use in a very humid climate. Possibly the many attempts made by the Feil Brothers‡ before success was achieved in the making of the crown element of the 91-cm objective had something to do with its sensitivity to weathering. Some types of crown glass are quite sensitive, and others are among the least sensitive to weathering, as the pertinent data in the Schott catalog quickly show. Also, insofar as standard achromatic objectives are concerned, it makes little difference which of the standard crown and flint glasses are combined. The secondary spectrum remains almost unaffected.[12]

Among the many smaller refractors these several defects and the secondary spectrum are less serious. However, for observation of planetary detail limited apertures on nights of fine seeing cannot possibly yield the results obtained with still larger apertures. It is true that on many nights the observer finds it expedient to reduce the aperture of his telescope to match the ambient seeing conditions. On the very best nights, nevertheless, one must agree with Antoniadi[13] that maximum aperture is vital for the very best results.

Many scientists in the field have preferred to use objectives of very great focal length, a device that for quite valid technical reasons reduces the effect of secondary spectrum on the angular resolving power of the system. Indeed, the observers of the 17th century were well aware of the optical advantages of using an increased focal length for a given aperture, which in their case had as much to do with ordinary spherical aberration as with the "primary" spectrum of their unachromatized systems.*

For practical reasons the largest refractors have been assigned focal ratios of the order of $f/15$ to $f/20$, even though from a scientific point of view, $f/30$ would be better. Considerations of cost and mechanical stiffness of tube have forced a compromise, not to mention the problem of building the large dome that a longer instrument requires. Frequently, the dome costs a substantial fraction of the value of the refractor itself. If the focal length is to be made greater and the dome all the larger, it is evident that the total expense will be high for a given aperture.

The refractors of highest focal-ratio among the largest objectives in the world appear to be the 68-cm $f/31$ refractor of the Berlin-Treptow Archenhold Observatory,† and the 60-cm $f/30$ Henry objectives of the Loewy coudé telescope at the National Observatory, Paris.‡ The Treptow refractor is used in the open air, and, even if the telescope itself were perfect, the high latitude and low elevation of the site mitigate against optimum observing conditions for planets and particularly for Mars at the closest oppositions. Indeed, even at Paris it is stated that only 10 nights in four years were found to yield fine seeing.**

Bernard Lyot was well acquainted with all the considerations affecting the performance of large refractors and indeed pioneered in many aspects of astronomical

* See ref. 8, pp. 61–62 and Plate II.
† See ref. 8, pp. 88–95.
‡ See ref. 7, p. 309.

* See ref. 11, pp. 17–18.
† See ref. 7, p. 308.
‡ See ref. 7, p. 432.
** See ref. 7, p. 380.

instrumentation. Some of his work would have served to optimize planetary telescopes in due course except for his untimely death. It did prove worthwhile to transfer the photographically corrected Henry refractor of 60-cm diam and $f/30$ focal ratio to Pic-du-Midi. In this instance the site is one of the best in the world, but even from the beginning of the observations the Henry objective has been "folded" with the aid of two optical flats to fit onto the Baillaud equatorial in place of the original 51-cm reflector. The two flat mirrors have been figured to be of especially good optical quality, but however flat they may be, there is always a significant amount of scattered light from the countless pinholes and microscopic defects in aluminum coatings. Here again, for planetary work at the very lowest contrast the use of two mirrors poses difficulties. One has only to consider the purity of the performance of the coronagraphic objective vs that of the coelostat in solar work.[14] In addition, any error in figure of a reflecting surface, whether inherent in the manufacture or caused temporarily by flexure or thermal changes, affects the distribution of light among the rings of the diffraction image by a factor of approximately 16 over what the same error in figure of a single refracting surface would produce. First of all, it is well known that the ratio of error in optical path between mirror and lens surface for the same mathematical departure from figure is as $2/(n-1)$ or, approximately, 4. It is less well known that the error in optical path affects the contrast rendition in the diffraction pattern as the square.[15] The two factors combined lead to a 16:1 ratio. Thus, while the Pic-du-Midi refractor at $f/30$ is probably as close to optimum as any other instrument and site combination in the world, comparing favorably with the Mount Hamilton 91-cm and the Flagstaff 61-cm refractors, one still cannot maintain that the optimum has been reached.

Apochromatism

As indicated earlier in this discussion, the mathematical principles underlying the nature of secondary and tertiary spectra were fully understood at a very early date (even possibly by Dollond).* The solution to the difficulty lay in the successful development of unorthodox optical materials (cf. early studies by Blair on liquid-filled objectives†). The fundamental work of Abbe in laying the theoretical foundations of microscopy also pointed out the desirability of the elimination of secondary spectrum in microscope objectives. Abbe himself introduced the fluorite objective that has greatly reduced residual chromatic aberration. However, optically sound natural fluorite was to be had only in very small pieces. We are more fortunate today in that optically satisfactory synthetic fluorite is available in disks up to 15-cm diam.* Abbe introduced the term "apochromatic" to describe an objective corrected parfocally for three widely separated wavelengths and corrected for spherical aberration and coma for two widely separated wavelengths.†

The term "apochromat" has been loosely used and misused over the decades by industry and scientific workers alike. While accepted as a criterion of quality, the word apochromat has created some confusion in optical writings. Some objectives sold as apochromats may be only partially improved, or indeed may be especially well corrected only for chromatic difference of magnification, an aberration that is quite different from longitudinal secondary spectrum and one that can be corrected even if only standard types of glass are used. Frequently, makers claim to have produced an apochromat when only the paraxial color curve has been improved, and when achromatized aplanatism may have been forgotten. The author prefers to retain Abbe's original definition and intent, subject to the comment that an objective may be taken to be apochromatic for a given purpose if its residual color errors for focus and aplanatism lie well within tolerances set by the diffraction behavior of light for the aperture, field, and spectral spread of interest. One might note too that some of the residual color curves obtained with combinations of glass and crystals or of crystals alone are too irregular to describe so simply as secondary, tertiary, quaternary spectra, and the like. On occasion one must reduce the sums of the squares of the weighted path errors to a minimum over an assigned spectral interval. However, in the simpler constructions and for normal spectral ranges for visual and photographic use there is little ambiguity in the use of the term apochromat.

Early in the development of new types of optical glasses the Jenaer Glaswerk Schott & Gen. began to introduce glass types that in combination with selected standard types served to reduce the secondary spectrum. The new "short flints" had dispersive powers too close to those of the mating crowns, however, and the resulting objectives either had excessively strong lens curves or were only partially corrected for secondary spectrum, unfortunately still more or less true. When the individual lens curves are strong, the designer must be all the more careful about correcting for spherical aberration and coma. Even so, the objective becomes all the more sensitive to misalignment and to thermal changes in the individual elements.

Hovestadt writes in 1900[16] of certain glass pairs

* See ref. 3, pp. 91–94, particularly by Clairant.

† See ref. 7, p. 189.

* Harshaw Scientific Company, Catalog of Synthetic Crystals, 1961.

† See ref. 12, p. 378. Possibly a fully designed Superachromat (ref. 9. Herzberger) might be called a "Herzberger Superachromat."

known then to yield correction in varying degrees such as:

		n_D	ν
S.30	Schweres Barium-Phosphat-Crown	1.5760	65.2
S 7.	Borat-Flint	1.6086	44.3
S 30.	Schweres Barium-Phosphat-Crown	1.5760	65.2
S 8.	Borat-Flint	1.5736	50.8
S 40.	Mittleres Phosphat-Crown	1.5590	66.9
S 35.	Borat-Flint	1.5503	55.2
O 225	Leichtes Phosphat-Crown	1.5159	70.0
S 35.	Borat-Flint	1.5503	55.2
O 60.	Kalk-Silikat-Crown	1.5179	60.2
O 164	Borosilikat-Flint	1.5503	49.4

Czapski already in 1886 had pointed out by calculation that the first pair given above is approximately half-corrected for secondary spectrum and that the second pair above is almost fully corrected for secondary spectrum. In this latter case the Schott types most nearly the same even today are listed as PSK-2 and KzFS-3. Dennis Taylor in 1893 wrote*: "... Dr. Czapski of Jena describes a form of objective of which two or three were made by Bamberg of Berlin, and also, I believe, by Dr. Czapski himself, in which the positive lens was made of Schott's dense barium phosphate crown S 30., and the negative lens of Schott's borate flint S 8. or S 7. This is somewhat similar to a combination of the same flint with a nearly similar crown which was carried out by Messrs. Cooke about seven years ago, and found to make a more than usually achromatic object glass. But the borate flints are too soft for practical purposes, and moreover, Dr. Schott has informed us that it is almost impossible to get good disks of this glass of over 5 inches aperture." Compare the situation today. One can now obtain disks of KzFS-4 glass corresponding to the S 7. Borat-Flint used above in diameters up to 72 cm for a 6 cm thickness.

Taylor also mentions that Hastings in America patented a form of object glass with reduced secondary spectrum in which he used Schott's O.13 and O.161 types.

O.13	Kalk-Silikat-Crown	1.5228	58.0
O.161	Borosilikat-Flint	1.5676	46.7

These types are related approximately to current Schott types of K-5 and KzF-4. Taylor adds that the crown is too hygroscopic and the flint, according to Dr. Schott, cannot be made good enough. Contrast this with today. K-5 is only mildly hygroscopic, and KzF-4 is available in disks up to 50-cm diam by 5 cm thickness.

In the same paper[17] Taylor gives his design for a triplet objective of Schott glass types, namely:

O.543	Baryt-Leichtflint	1.5637	50.6
O.164	Borosilikat-Flint	1.5503	49.4*
O.374	Silikat-Crown	1.5109	60.5

The Schott glass types nearest today to those used by Taylor are BaLF-1, KzF-1, and K-7. All are quite durable with respect to moisture and are almost free of coloration. Taylor correctly points out that the KzF-1 type would not be safe to use as an exterior lens for an objective to be located near a city using coal, or in a sulfureted hydrogen atmosphere. KzF-1 today can be procured in sizes up to 75-cm diam for a 6-cm thickness.

The Schott Company has kindly granted the author permission to publish Table II from data supplied in correspondence. It should be noted that these values will necessarily fluctuate as experience grows and according to budgetary allowances. It is obvious that, if one can afford to make a dozen attempts for a disk larger than any made heretofore, success is more certain than if only one try is made. Conversely, if a successful disk is demanded as a result of only one or two tries, the glass manufacturer is bound to restrict the promised diameter to lie well within his experience. The glass types given in Table II are among those likely to be useful for precision astronomical objectives for astrometric and astrographic purposes.

Table II. Maximum Volume List for Selected Types as of November 1961

Glass type	Maximum volume (liters)	Maximum diameter obtainable for 3 given thicknesses		
		60 mm	80 mm	115 mm
PSK-1	50	102.5 cm	89.0 cm	74.5 cm
BK-7	100	146.0	125.5	105.0
ZK-2	75	125.0	109.0	91.5
BaK-2	75	125.0	109.0	91.5
SK-2	50	102.5	89.0	74.5
SK-11	50	102.5	89.0	74.5
BaLF-3	50	102.5	89.0	74.5
BaLF-6	50	102.5	89.0	74.5
F-2	65	118.0	102.5	85.0
KzF-5	50	102.5	89.0	74.5
KzFS-2	25	72.5	63.0	52.5
KzFS-3	25	72.5	63.0	52.5
KzFS-4	25	72.5	63.0	52.5

Semiapochromats and Apochromats

For a great many decades the Carl Zeiss Company of Jena and now of Oberkochen, West Germany, has listed three types of telescope objectives. The E-objectives are of the Fraunhofer type and have the normal secondary spectrum. The AS-objectives are doublets with flint leading and are thought of as "half-apochromats" or semiapochromats. The B-objectives

* See ref. 8, p. 80.

* Taylor mentions that the actual negative lens was to be made of a related Schott type with refractive index n_D of 1.547.

are triplets and are called full apochromats, if manufactured at $f/15$, but are still semiapochromats if manufactured at $f/11$. Then, in recent years an F-type objective of apochromatic correction has appeared for use at $f/11$, an objective that makes use of a very high index flint glass as a third-element positive lens, corrected chromatically by a hyperchromatic pair of somewhat lighter glass types.

The Zeiss (König) B-objectives are in reality improved Taylor objectives making use of BaLF-4, KzF-5, and K-7.* The latter two glass types are available in large diameters in objective grade as indicated in Tables I and II. BaLF-4, which is not listed in the Tables, is given separately as available in a maximum volume of 15 liters in objective grade or in a volume of 40 liters in plattenglas. Thus, if some light striae were to be permitted, an objective as large as 75-cm clear aperture of apochromatic quality can be made.† It is to be noted once again, however, that in such a triplet objective the internal dioptric powers are great and that the objective will remain sensitive to misalignment, flexure, and thermal gradients. Such Zeiss objectives in diameters of the order of 15 cm have been mounted with glass separators made by optical methods to hold the elements in true center. The separators and associated elements fit inside the usual metal cell.‡

One might mention here that the badly neglected Schupmann form of catadioptric telescope[18] employs but a single large front element of crown glass and that the optical power of this one element amounts only to about 40% of the power usually associated with the crown element of the normal achromatic objective. In addition, the single element can be given a form free of coma which renders it extremely insensitive to first-order bendings or to flexure.[19] Thermal gradients will be small and will have far less effect on the performance of the Schupmann objective than in the case of the ordinary doublet. The crown element of the Fraunhofer objective, in point of contrast, is not of itself corrected for coma and apart from its great individual lens power is sensitive to flexure because of that coma. In principle, a Schupmann catadioptric telescope can be made today in a diameter of at least 152 cm and probably even larger. A BK-7 or ZK-2 Schupmann objective lens in, say, a 12-cm thickness would have much better transmission, particularly in the violet and ultraviolet, than that of the Yerkes objective. (See Table VI.) Finally, the secondary spectrum of the Schupmann can be eliminated altogether. Indeed, the Schupmann is nearly as free of color aberration as the reflecting telescope. However, the Schupmann type of telescope is not to be thought of here as the ideal solution for a planetary telescope for observations of extremely low contrast.* There are too many surfaces overall, there is one reflection to help spoil matters, and the tube is either very long for the focal length or else additional surfaces have to be added. The Schupmann does happen to be the most nearly perfect telescope mathematically and can be built in very large diameters at a cost substantially lower than for doublet or triplet refractors of the same clear aperture. The Schupmann telescope does offer promise as a combined refractor and coronagraph.[20]

It is not the author's intent here to explore the precise history of the apochromatic refractor. To do so would be a very long, though interesting, assignment, and to be complete one would have to seek out the private files of many older optical firms. In general, the planetary observers of the last two centuries have been fully aware of the desirability of obtaining refractors with the quality of an apochromat but have been blocked in their efforts, either by the lack of adequate special glass types in large diameters at an acceptable price, or in later years by the fact that various objectives claimed to be apochromats were not actually adequately corrected in the Abbe sense. One must stress again that the color correction of the apochromat will not yield its full advantage over that of the achromat unless spherical aberration, coma, alignment, and glass quality are under equally good control.

Gerard de Vaucouleurs has kindly brought to our attention the existence of a 52-cm objective purchased by Jarry-Desloges for use in his private observatory in Algeria around 1912. While this objective was intended originally to be a true apochromat, one must conclude from the description that it is at most a semiapochromat.[21] ("...car les indices de ces verres, quoique permettant une correction meilleure que le moyenne pour certaines parties du spectre, sont bien loin de permettre l'elimination du spectre secondaire.") This objective was indeed built, however, at a focal ratio of $f/12$, which choice alone, though forced by consideration of the cost of the mounting and dome, led to an optical performance as a semiapochromat not much better than that of a standard 52-cm $f/20$ achromat. Jarry-Desloges nevertheless was very pleased with the performance of this Schaer objective. The objective was stored away during World War I. In a preliminary library search it is not clear to the author what may ever have happened to this objective since then.

Many smaller apochromats have been built over the years. In recent years the largest objective known to the author as a true apochromat in the Abbe sense is the 38-cm apochromat built for the Ottawa Observatory to an optical design by Lloyd McCarthy. This triplet of the Taylor type uses the Chance-Pilkington Borate-

* See ref. 3, pp. 241–242.

† See ref. 17, p. 337.

‡ See also ref. 9 (Stephens, 1960).

* Yet cf. ref. 3, p. 270.

flint for the negative element, a glass type similar to KzFS-4. The author has been informed of plans for a 51-cm apochromatic refractor to be mounted in West Texas. The objective is now nearing completion at the Tinsley Laboratories in Berkeley, California.

The Zeiss Company at the time it was in Jena had a very large objective of its own used as a collimator lens in an underground testing laboratory. It is not known to the author whether this objective might have been a semiapochromat, although it is very doubtful. Finally, it is interesting to note that some disks of 127-cm diam were made by M. Mantois for the Paris Exposition of 1900 for both photographic and visual doublets. While not in any way apochromatic the objective was chosen to be $f/45.6$ for the purpose of minimizing the effect of secondary spectrum on angular resolution and contrast. In view of the near hopelessness of having a dome for a telescope 57 m long, the makers MM Mantois and Gautier provided a single large flat mirror of 2-m diam as a siderostat.* The entire effort was by no means a small one, and much careful work by Gautier went into the mounting for telescope and siderostat. Antoniadi was very much impressed with the excellence of the drive. The telescope is now completely dismounted, and the objectives are stored away. Similar disks are in existence at the Parra-Mantois & Co. in Le Vesinet, France, and would be available to a qualified buyer.

The question now arises as to where matters stand if one really wishes to have a planetary telescope making use of all the recent technological advances. The refractor has fallen out of favor where new telescope projects are concerned, except for the important application as a coronagraph, and most astronomers and astrophysicists would frown upon any revival of the subject. However, the fact is that parallax and proper motion astrometric astronomy can gain from having improved objectives designed for their highly specialized purposes where engineering improvements are at least as important as the optical ones. For the subject at hand, the planetary observer interested in visual observation of very low-contrast detail on Mars and other planets can still profit by having a precision telescope available that is essentially free of secondary spectrum and of other difficulties outlined above.

Any actual project involving the design and fabrication of a large apochromat would require the closest cooperation between designer and glass makers. It might well be that a number of optical designs would have to be carried through and presented to the glass manufacturers who in turn could undertake a program for experimental development of the most promising combinations. For the time being, any such design study is bound to be preliminary. Nevertheless, it may be of interest here to look at the possibilities of a few design forms that might offer a satisfactory compromise between some good state of correction for secondary spectrum and resistance over long periods of time to atmospheric deterioration of the lens surfaces. Indeed, in 1938 when the author first became interested in apochromatic objectives, a least squares solution was made of all the available Schott glass types of the time (about 155 in all), of all the Bausch & Lomb glass types, and of a great many of the Parra-Mantois types. The results of the least squares study made it a relatively easy matter to choose combinations of glasses having reduced or negligible secondary spectrum.[22] In 1938 the author designed a triple objective essentially of the Taylor form, corrected for secondary spectrum, and for aplanatism for two colors, all in the sense of the true apochromat. The first such objective was built in 1940 for the Harvard Observatory and performed satisfactorily except for a slight diffuseness of image caused by inadequate glass quality. In recent years this same objective somewhat improved has been built as a 12.5-cm $f/15$ sighting telescope. The internal curves are of large dioptric power, and hence the sensitivity to misalignment is fully comparable to that of the original Taylor and König apochromats discussed earlier.

The author in 1944 discovered quite independently the use of the high-index flint glass as a positive element in an apochromat of the F-type manufactured in recent years by the Zeiss Company. The discovery was forced by the search for apochromatic combinations with then available domestic glasses. The striking thing about the combination of the high-index flint as a positive element with an hyperchromatic pair of normal crown and flint glasses is that the secondary and tertiary spectra are both eliminated. The resulting quaternary spectrum is of no real consequence unless one must include the deep violet and the near infrared.* The principles have also been put to use in the design of periscopes having quite satisfactory correction for color aberrations. The objective is handicapped in other respects, however, such as large internal powers, the coloration of the high-index flint, and the sensitivity of the high-index flint glass to flexure owing to its high specific gravity.

A number of glass types have been reviewed by the author with respect to the particular problem of a planetary telescope of improved performance. For the negative element or elements of an objective the study included the special flints such as KzF-1, KzF-2, KzF-3, KzF-4, KzF-5, and KzF-6; and KzFS-1, KzFS-2, KzFS-3, and KzFS-4. Even more remote possibilities such as ZK-7 and the lanthanum glasses were considered.

Among the special flints KzF-5, KzFS-2, and KzFS-4

* See ref. 7, p. 433.

* Herzberger has now fully explained the theoretical reasons and relationships involved and has indicated that substantial improvements are possible. See ref. 9 (Stephens 1960).

seem to be the most promising for objectives no more complicated than triplets. KzFS-1 is somewhat superior to KzFS-4 with respect to correction for secondary spectrum in combination with appropriate standard types, but is no longer manufactured. However, KzFS-4 has the same index and dispersion, and is somewhat more stable. KzF-5 is a glass having a greater stability than KzFS-4 in turn, and is more usable in doublet combinations. KzFS-2, while comparatively excellent for the reduction or elimination of secondary spectrum, is quite hygroscopic and can be used only between protective elements of resistant types of glass for instruments likely to be exposed to the atmosphere for prolonged periods. KzFS-2 appears to be a bit freer of coloration than KzFS-4 in the disks seen by the author. As long as triplet objectives must be employed, either with KzFS-2 or KzFS-4, for the present purposes, the author has chosen the former.

If a Ross-type four-element lens were to be designed for photographic purposes in a semiapochromatic or fully apochromatic form, very likely it would be necessary to use KzFS-4 for the negative elements, protected as they are by the outer positive elements. The mating glass type might be SK-2, for example, for a semiapochromat, but the f/number would have to be $f/20$ or slower, according to the focal length. An improved color correction tending toward apochromatic could be obtained with SSK-1 or better SSK-2 combined with KzFS-4 in a Ross lens but the individual lens powers would be substantial. A combination of SSK-3 with KzFS-4 would tend toward apochromatic correction favoring blue light a bit more, but the individual lens powers would be all the greater. One can instead use a pairing of SK-5 and KzFS-2 for an apochromatic Ross lens but the f/number would possibly have to be $f/20$ or slower for optimum results. The great tendency of KzFS-2 to undergo atmospheric attack would also be a disadvantage, even in a sealed cell. If faster apochromatic objectives are to be desired, a combination of SK-5 and KzFS-2 glass types in the Dynar form would be found effective, particularly in view of the fact that the thermal coefficients of expansion are comparable and small (for SK-5, 6.0×10^{-6}; for KzFS-2, 5.3×10^{-6}). This long-established form of photographic objective, also called the Pentac, employs five elements in more or less symmetrical array. Elements 1 and 2, and 4 and 5 are combined in doublets that for small systems can be cemented together to minimize the number of air–glass surfaces. Element 3 is a negative biconcave element in a central location. Such a system is particularly effective for apochromatic design where the negative power of the system is broken down and distributed among three elements that offset the positive power divided between two elements. A detailed design leads to an objective of full astronomical quality that might be effective in astrometric work requiring large fields substantially free of distortion and other asymmetrical errors.

It may be interesting to mention that KzFS-2 in combination with SK-14 was used for the correcting plate trio in the optical system for the Smithsonian satellite tracking cameras for the purpose of obtaining full apochromatic performance at $f/1.0$. While the hygroscopic characteristics of KzFS-2 are very unfavorable, regrettably this combination was the only one that could satisfy the stringent requirements on optical performance and transmission. KzFS-4 might have been used in combination with SSK-5, a glass much more hygroscopic in turn than the SK-14 actually used. Such a pairing, however, would have been inefficient in the near ultraviolet. KzFS-3 might have been used in combination with SK-15, but KzFS-3 is even more subject to atmospheric attack than KzFS-2. While the surface deterioration is essentially proportional to the exposure, it is possible to slow down the rate of attack by "rubbing-down" the glass when it first begins to show surface coloration. Indeed, on sample blocks of KzFS-2 the author was unable to increase the deterioration of a rubbed-down surface even after it was subjected to exposure in a steam cabinet for a full week. The sample showed no apparent loss of light by transmission, and the surface discoloration was visible only by reflected light. On the other hand, rain water and dew cause more immediate attack than tap water owing to the presence of CO_2 in the air. A sample of KzFS-2 exposed to damp air or dew for long periods will develop a hazy white surface layer that in some cases can be washed off with delicate handling, but in others adheres firmly to the glass. Nonreflection coatings tend to retard the atmospheric attack, but for large precision elements it is unsafe to heat them to a temperature sufficient for hard coatings to be obtained.

The lanthanum rare earth glass types can be used to achieve semiapochromatic or full apochromatic performance in combination with suitable standard glasses.* The author has not included these in the present study in the belief that they would not be particularly effective for large planetary telescopes even though available in some types in fairly large diameters. (See Table I.) Most of these glasses are at least as subject to atmospheric attack as KzFS-2 and on the whole would have somewhat reduced transmission in large thicknesses. Cost and thermal expansion are other factors that must be considered. In addition, the lanthanum glasses have specific gravities in the neighborhood of 4, as compared to 2.7 for KzFS-2. Used necessarily as negative elements in spite of their high indices of refraction, lanthanum elements would be heavy and subject to flexure. Nevertheless, for systems of small

* See ref. 9 (Stephens, 1959, p. 400).

to medium diameters one cannot overlook the fact that rare earth glass types can be very useful.

Comparison of a Few Combinations of Glass Types

The final precise residual color aberration of an objective is to some extent affected by design choices of thicknesses, air-spaces, and lens curves. In order to achieve an exact comparison on as simple a basis as possible, the author has calculated a standard achromat, three glass semiapochromats, and one glass-fluorite apochromat, where all elements are taken to be of zero central thickness.* For this purpose the word apochromat provisionally will have to be loosely used on the understanding that any actual lens on careful design would receive a final designation of semiapochromat or full apochromat according to the results achieved.[23] The color curves are derived purely from paraxial calculations in which F and C are held exactly parfocal where only two kinds of optical materials are involved, and where F, C, and A′ are held exactly parfocal for objectives using three kinds of optical materials. There are many pairings possible with KzFS-2, or with KzF-5, or with KzFS-4 from among readily available glass types that would yield more strictly apochromatic performance for the yellow-green optimum, but all of these will lead to stronger internal lens powers. In many cases the glass type for the positive element may also be subject to atmospheric attack or may lack good transmission. Finally, PKS-1 has been chosen among the possibilities because of its low coefficient of thermal expansion.

In Table III the criterion of correction for color curve is given in terms of the longitudinal focal error converted to the number of Rayleigh limit tolerance units arrived at on the basis of a standard $f/25$ objective of 51-cm clear aperture for all combinations. Table III shows that the apochromats are markedly superior to the achromat. Here again, only the last combination is fully apochromatic in the sense that the secondary spectrum is reduced to a tertiary spectrum, as shown by the negative residuals in the deep red. The irregularities in the trend of residuals are caused by the fact that the indices of refraction are available only through the 5th place in the glass catalog. The plus sign means that the wavelength involved focuses farther from the objective than the mean focus. The mean focus in turn is taken to lie 0.8 Rayleigh limit from the "smoothed-out minimum focus." Of course, any slight refocusing will reduce some residuals and increase others, but for purposes of comparison a consistent procedure has been adopted for all systems.

Table III shows that a normal achromat constructed as a 51-cm $f/25$ objective yields a performance already 5 Rayleigh limits in error at 4861Å and 3.7 Rayleigh limits at 6563Å. For a 51-cm $f/15$ objective one would find the respective errors to be 12.8 and 9.5 Rayleigh limits, where the increase is due to the fact that the Rayleigh tolerance depends on the square of the focal-ratio. Obviously, the standard achromat in large sizes is woefully deficient except in a very narrow wavelength range around the minimum focus.[24] Yet the giant refractors of the world are all afflicted with this grievous color aberration.*

Table III. Color Curves of Selected Combinations

Wavelength designation	Standard achromat BK-7 F-4	Doublet apochromat ZK-2 KzF-5	Triplet apochromat PSK-1 KzFS-2 PSK-1	Triplet apochromat BK-7 KzF-5 BaLF-6	Triplet apochromat BK-7 CaF_2 K-10
4047 (h)	57.4	21.1	24.3	20.3	8.1
4358 (g)	25.5	7.7	9.3	8.2	1.5
4800 (F′)	6.0	4.4	−0.4	0.7	
4861 (F)	5.0	2.6	−0.1	2.0	−0.2
5461 (e)	−0.8	0.0	−0.8	−0.3	−0.8
5876 (d)	−0.6	−1.0	−0.4	−1.0	
5893 (D)	0.1	−0.8	0.1	0.5	0.4
6438 (C′)	2.9	0.8	−1.0	0.7	
6563 (C)	3.7	1.9	0.0	1.5	−0.1
7682 (A′)	11.5	2.4	0.8	1.3	−0.1
10,140	31.3	4.8		6.9	

Table III also shows that the combination of PSK-1 and KzFS-2 is best among the several glass groupings under consideration, but that the fluorite objective is excellent even into the violet. (With KzFS-2 one would find that any of the types BK-2, BK-6, K-1, K-6, K-7, K-8, K-9, K-11, BaLK-1, BaLK-2, BaLK-3, ZK-2, SK-5, SK-11, SK-14, and SK-16 would all yield more nearly apochromatic color curves according to the spectral range of greatest interest, but as pointed out before, would have stronger internal lens powers and an assortment of advantages and disadvantages.) Unfortunately, fluorite cannot be obtained at present in diameters larger than about 15 cm. Even if larger diameters were to become available, extreme hazards are involved in handling such disks. Fluorite is expensive, and fluorite lens elements are far more subject to breakage than glass elements. The low index of refraction leads to a strong biconvex form for the fluorite element. Fluorite has a large thermal coefficient of expansion, and is mechanically weak. Thus, any slight cooling of a fluorite element will cause the thin, weak periphery of the element to contract rapidly around the warmer, more voluminous center region, whereupon breakage may ensue. The fluorite apochromat is therefore an objective with mixed blessings. Its inclusion in Table III as a 51-cm $f/25$ objective is purely for purposes of intercomparison.

Table IV gives the calculated paraxial focal displacements from an adopted mean for each combination.

* See ref. 9 (Stephens, 1960). (Unfortunately, PKS-1 is not yet available in objective grade at all, and to only an 80-mm diam in plattenglas.)

* See ref. 11, p. 91.

Table IV. Color Curves in Terms of Focal Displacement

Wavelength designation	Standard achromat BK-7 F-4	Doublet apochromat ZK-2 KzF-5	Triplet apochromat PSK-1 KzFS-2 PSK-1	Triplet apochromat BK-7 KzF-5 BaLF-6	Triplet apochromat BK-7 CaF_2 K-10	Schupmann ZK-7 (with PKS-1 and KzFS-2)
4047 (h)	0.004590	0.001687	0.001944	0.001620	0.000649	0.000029
4358 (g)	0.002197	0.000660	0.000801	0.000703	0.000126	0.000000
4800 (F′)	0.000564	0.000409	−0.000035	0.000066		−0.000010
4861 (F)	0.000484	0.000249	−0.000005	0.000191	−0.000016	−0.000011
5461 (e)	−0.000086	0.000000	−0.000090	−0.000028	−0.000086	−0.000011
5876 (d)	−0.000074	−0.000115	−0.000047	−0.000116		−0.000007
5893 (D)	0.000009	−0.000096	0.000008	0.000053	0.000048	−0.000008
6438 (C′)	0.000362	0.000098	−0.000127	0.000085		−0.000002
6563 (C)	0.000483	0.000249	−0.000006	0.000191	−0.000016	0.000000
7682 (A′)	0.001742	0.000358	0.000119	0.000191	−0.000016	0.000009
10140	0.006269	0.000962		0.001383		

The displacements are in units of the focal length. The Schupmann telescope is added for purpose of comparison. The field lens for the Schupmann is taken to be a semiapochromatic combination of PKS-1 (available currently only up to 80-mm diam and 25-mm thickness in plattenglas) and KzFS-2. If a full apochromat were to be used, the residual color curve would be all the better corrected.

In Table V a further comparison is made between the several systems with the strictest needs of a planetary telescope in mind. For the first four combinations a least squares solution has been made with respect to the wavelengths F′, F, e, d, D, C′, and C; for the fluorite objective a similar solution has been determined, but only for the wavelengths for which exact indices of refraction are at hand. Weighting factors have been assigned in a somewhat arbitrary though pertinent way. It is assumed that for fully satisfactory results for purposes of planetary observations, F′ should not be in error by more than 1.0 Rayleigh limit, F by more than 0.9, e by more than 0.1, d by more than 0.1, C′ by more than 0.3, and C by more than 0.5 Rayleigh limit at the respective wavelengths.

Having completed the least squares solution at the optimum focal setting for each combination, one can then determine what f/number would be required to meet the above designated stringent requirements on residual errors in terms of the respective Rayleigh limits. Table V gives the f/number so derived and the residuals in terms of Rayleigh limits against wavelength produced by the newly determined f/number.

There is some margin of uncertainty about the f/numbers so derived in view of the irregularities in residuals produced by the large internal lens powers as exaggerated from small round-off or interpolation errors in the fifth decimal place in the glass catalog. Nevertheless, it is evident from Table V that the standard achromat at f/18 as normally constructed lies far from the critical limit of performance adopted here for an idealized planetary telescope. Conversely, while an f/163 focal ratio will yield the desired performance in the case of the standard doublet, the associated focal length of 83 m for the 51-cm aperture is impossibly long for any practical consideration. The triplet combination of PSK-1 and KzFS-2 (i.e., with KzFS-2 encased between outside elements of PSK-1) shows up best except for the Schupmann and yet at f/62 would still have a focal length of 31.6 m for a 51-cm aperture. One should note that the Schupmann

Table V. Comparison of Selected Glass Combinations in Terms of Focal Ratio for Similar Performance

Wavelength designation	Standard achromat BK-7 F-4 f/163	Doublet apochromat ZK-2 KzF-5 f/112	Triplet apochromat PSK-1 KzFS-2 PSK-1 f/62	Triplet apochromat BK-7 KzF-5 BaLF-6 f/109	Triplet apochromat BK-7 CaF_2 K-10 f/106	Schupmann ZK-7 (with PKS-1 and KzFS-2) f/20
4800 (F′)	1.0	1.1	−0.1	0.2		0.0
4861 (F)	0.8	0.7	−0.2	0.5	0.0	0.0
5461 (e)	−0.1	0.1	−0.2	0.0	−0.1	0.0
5876 (d)	−0.1	−0.1	0.0	−0.2		0.0
5893 (D)	0.1	−0.1	0.2	0.1	0.1	0.0
6438 (C′)	0.5	0.3	−0.3	0.2		0.0
6563 (C)	0.6	0.5	−0.1	0.4	0.0	0.0

Table VIa. Transmission Data for a 25-cm Thickness (Surface Reflections Excluded)

Wavelength	BK-7 (mean value)	ZK-2 (melt Z 10019)
3650	0.70	0.749
4000	0.88	0.920
4047	0.89	0.925
4358	0.91	0.902
5461	0.95	0.949
5780	0.95	0.947
5820	0.95	0.943
7000	0.95	0.952

at $f/20$ has an over-all length in a straight line corresponding to a doublet of focal ratio about $f/30$, on the average, and hence is still a difficult telescope to mount. In Table V the fluorite objective does not appear to be quite so superior for visual use as is indicated in Table III. However, data for only four wavelengths are available, a fact that adds to the uncertainty. The data in Table V are sufficiently reliable, however, to place the PSK-1 and KzFS-2 triplet clearly in the lead insofar as all-glass combinations are concerned among the few examples presently considered. For a wider spectral coverage one should recompute the above table. Then, undoubtedly, the fluorite combination would take the lead except for the nearly perfect Schupmann system.

One should remember that there are other more favorable combinations with KzF-5 or KzFS-2 as negative element if only color correction is to be considered. (Note again the Herzberger Superachromats.) (Other possible positive elements for combination with KzFS-2 have already been listed. With KzF-5 one might use BaLK-1, K-2, K-3, K-4, K-5, K-6, K-7, K-8, K-9, K-10, ZK-1, ZK-3, ZK-4, BaK-2, BaK-5, SK-3, SK-4, SK-13, SK-14, and SK-15 for pairings as good as or better than ZK-2 according to the problem. In general the lens powers will be greater, except for BaLK-1, BaLK-2, K-6, K-7, K-9, and SK-14, with an assortment of other advantages and disadvantages.)

The combinations used here are intended to have either BK-7, ZK-2, or PSK-1 as the front element. All three of these glass types are very stable and are available in large diameters. (See Table II.) ZK-2 particularly is given in the catalog as one of the very few glass types having maximum resistance to both moisture and acids. The white light transmission of ZK-2 is excellent. Indeed, it will be of interest here to tabulate transmission data supplied the author by the Schott Company for another, quite different application, with the kind permission of the Company.

Table VIb. Transmission Data for a 10-cm Thickness (Surface Reflections Excluded)

Wavelength	PSK-1	BK-7	ZK-2	BaK-2	SK-11 (mean)	BaLF-3	BaLF-6
4358	0.931	0.952	0.960				
4861				0.977			
5000					0.966	0.983	0.978
5200				0.983			
5461	0.974	0.983	0.979	0.985	0.972	0.987	0.984
5780	0.970	0.983	0.978	0.982	0.970	0.984	0.980
5820			0.977				
6000		0.983					
6200	0.963	0.983		0.978	0.967	0.975	0.980
7000	0.965	0.983	0.981		0.966	0.975	0.980
7600				0.980			

Wavelength	SF-2	SF-4	SF-5	SF-6 FA	KzF-5	KzFS-2	KzFS-3	KzFS-4 (mean)
4358				0.74	0.808	0.918		
4861		0.954						
5000	0.970		0.981				0.985	0.964
5200	0.974	0.981						
5461	0.989	0.989	0.992	0.987	0.968	0.979	0.984	0.968
5780	0.990	0.988	0.992	0.988	0.968	0.974	0.977	0.960
6000		0.983		0.981				
6200	0.985					0.965	0.971	0.954
6600		0.980		0.981				
7000		0.992	0.993	0.988		0.954	0.959	0.945
7600		0.996		0.995				
7800	0.993							
8000		0.994		0.995				
8200	0.992							

If a doublet making use of ZK-2 and KzF-5 were actually to be fabricated as a 51-cm clear aperture $f/30$, it is likely that the central thickness of either element would not exceed 8 cm. Accordingly, from Table VI it would appear that the pure transmission through such a doublet in visual light would be of the order of 96%. The combined residual surface losses after coating would probably bring the over-all transmission in visual light down to a final figure of about 88%. Such efficiency compares very favorably with the reflectivity of a freshly coated single mirror surface.

In summary it should be recalled that the discussion here is centered around glass combinations of interest for planetary telescopes of medium to large clear apertures. The subject of the reduction or elimination of secondary spectrum would become a much broader one if other applications in optics were to be considered.* In particular, solutions proposed for improved color correction for small optical systems used under laboratory conditions may not be at all useful for large telescopes exposed to the atmosphere under a wide range of conditions of temperature and humidity. Improved solutions often lead to unacceptably large internal lens powers that for large telescopes would create new difficulties nearly as bad as the secondary spectrum. Multiple-element solutions in principle have been known for a long time but are subject to considerable improvement.[25]

One must remember that the over-all design of an apochromat must continue to eliminate spherical aberration, coma, and the chromatic variants of each within close tolerances. Finally, it should be noted once again that the five significant figures given in glass catalogs at present contain round-off errors or may have been arrived at in some cases by the use of somewhat inexact interpolation formulas. If a multiple-element solution contains large internal powers, these powers numerically will be extremely sensitive to small changes in the fifth decimal place. Conversely, improved apochromats, calculated from inaccurate data, in practice may turn out not to be much improved. It would be best if the glass companies could provide reliable data to the sixth decimal place for systems intended to be apochromatic within a known fraction of a Rayleigh limit for each standard wavelength in the desired spectral range.

At one time or another over the years since 1938 the author has calculated a variety of designs for ordinary achromats, semiapochromats, and full apochromats. Some of these designs have been much more elaborate in nature than simple doublet or triplet telescope objectives and have been intended for wide-field photographic usage over extended spectral ranges. Of interest here is the fact that many of the systems with improved color correction have made use of fluorite, KzF-5, KzFS-2, and KzFS-4. No one material will satisfy all needs, where one must take into account physical environment, aging, mistreatment, transmission, cost, higher-order aberrations, or maximum performance for minimum weight.[26]

Examples

It may be of interest here to some readers to reproduce several designs from past projects that are related to the discussions above. No formula is given for the Schupmann system.* The reader is cautioned to note that, while the designs below can be scaled and made usable for a number of applications, they may not be optimum for any one special purpose. An appreciable change in focal ratio will affect such an optimum. Any change in the wavelength region of optimum correction will also require a redesign according to the extent of the change.

1. Fraunhofer-Type Objective. Given as a 51-cm $f/15$ objective here, but can be scaled to other focal lengths and apertures.†

		Separations	
Surface	Radii (mm)	Glass (mm)	Air (mm)
1	4635.	53.64	
2	−2700.3		0.38
3	−2732.0	38.30	
4	−11381.		7575.[a]
Surface	n_D	ν	Type
1	1.517	64.5	BSC-2 (B&L)
3	1.617	36.6	DF-2 (B&L)

[a] Back focus (i.e., the distance along the optical axis from the rear lens vertex to the focus).

Remarks: This objective is the usual Fraunhofer type with "broken contact." The objective is corrected for F and C at the 0.707 zone of the aperture, and is corrected for the rim ray at $f/15$. The residual errors comprise the normal secondary spectrum, and a very weak zonal spherical aberration that is well within tolerance but which can be removed altogether by a slight amount of aspheric figuring. The coma is fully corrected.

2. Air-Spaced Objective with Equal Internal Radii. Given as a 51-cm $f/15$ here, but can be scaled to other focal lengths and apertures.†

* See ref. 9, Herzberger.

* See ref. 20, p. 83; ref. 18; and ref. 3, p. 269.

† See ref. 10, p. 29. Note that "51-cm" refers to the clear aperture and not to focal length, which is astronomical practice.

Surface	Radii (mm)	Separations: Glass (mm)	Separations: Air (mm)
1	4431.	52.83	
2	−2731.8		23.70
3	−2731.8	37.74	
4	−12336.		7519.

Surface	n_D	ν	Type
1	1.517	64.5	BSC-2 (B&L)
3	1.617	36.6	DF-2 (B&L)

Remarks: This objective is corrected for F and C at the 0.707 zone of the aperture, and is also corrected for the rim ray at $f/15$. The residual errors are the normal secondary spectrum, and an almost negligible zonal spherical aberration. Chromatic spherical aberration is also very small. The coma is fully corrected. The air-space is only about one-fourth that of the Clark objective. However, the above objective has the advantage of equal radii for the critical surfaces, a situation that will be of convenience to an optician. Slight adjustments in air-spacing of the finished objective will compensate for residual errors of manufacture.

It is a pity that some of the large refractors have residual coma.[27] This situation is by no means necessary and is a direct result of inadequacy of design. The objective designs given above are essentially free of coma and yet offer nothing new indeed since Fraunhofer's time insofar as aplanatism is concerned.

3. Cemented Semiapochromatic Doublet. Given here as a 51-cm $f/30$ objective, but can be scaled to other focal lengths and clear apertures.

Surface	Radii (mm)	Separations: Glass (mm)	Separations: Air (mm)
1	8922.	97.82	
2	−1099.	58.70	
3	−67975.		15149.

Surface	n_D	ν	Type
1	1.5209	60.22	ZK-2 (Schott)
2	1.5213	52.76	KzF-5 (Schott)

Remarks: The large aperture of 51 cm has been adopted here for purposes of comparison. Nevertheless, from all previous experience it has not been possible to "cement" telescope lenses together in diameters larger than about 15 cm. Changes in temperature will be transmitted only rather slowly throughout a thick cemented pair, and the air surfaces may "warp," owing to stresses set up by differences in thermal expansion between cement and glass. The glass elements in many cases also differ in thermal expansion.

The same problems undoubtedly will arise with the above objective in large diameters. However, liquid cements are now available that have exceedingly low vapor pressures and that can be as fluid or viscous as one chooses. The above objective has been designed with fairly thick elements in anticipation that such a liquid cement will be used. Whether the thermal problems can be alleviated for diameters greater than 25 cm will have to rest with experience. ZK-2 has a thermal expansion of 8.6×10^{-6}. KzF-5 has a coefficient of 5.9×10^{-6}.

If so large an objective as given in the basic tabulation cannot be oiled or cemented with liquid cements, at worst it will have the usual four air–glass surfaces. The objective is free of coma, but will have to be figured to remove the spherical aberration of third order still remaining at $f/30$. The negligible difference in index at the cemented interface means that there is no other way to achieve spherical correction. At $f/30$ the figuring required, however, will not be severe.

The chromatic residuals are:

Wavelength	Focal displacement	Semiapochromat (R.L.)	Standard achromat (R.L.)
4047 (h)	0.002101	21.9	46.4
4358 (g)	0.000936	9.1	21.1
4800 (F′)	0.000551	4.9	5.5
4861 (F)	0.000376	3.3	4.7
5461 (e)	0.000000	0.0	0.0
5876 (d)	−0.000182	−1.3	0.1
5893 (D)	−0.000167	−1.2	0.7
6438 (C′)	−0.000033	−0.2	2.8
6563 (C)	0.000104	0.7	3.5
7682 (A′)	0.000121	0.7	9.6

The above residuals for the semiapochromat do not appear favorable for d and D. Here one must state again that the strong internal lens powers of the semiapochromat exaggerate the round-off errors in the glass catalog compared to the effect of the moderately low internal powers of the achromat. From experience one notes that the correction for secondary spectrum is smoother in the e, d, and C regions than the figures would indicate. An astronomer should not be frightened away from the semiapochromat on such an account, even though it would be wise to obtain data to the sixth decimal place before procuring expensive disks of optical glass. The advantage of the semiapochromat over the achromat is clearly shown in the blue-violet and deep red.

The design given above is bordering on that of a full apochromat. With controlled figuring of the two air surfaces, one can indeed correct for chromatic spherical aberration precisely at $f/30$ without drawing on any unusual optical skills. The chromatic coma will

already be very small. The drastic improvement in color correction at the A′ line indicates that it might be reasonable to designate the design as apochromatic, even though no actual zero in focal displacement or reversal in sign has occurred.

4. Air-Spaced Semiapochromatic Doublet. Given here as a 51-cm $f/30$, but can be scaled to other focal lengths and clear apertures.

		Separations	
Surface	Radii (mm)	Glass (mm)	Air (mm)
1	7854.7	97.69	
2	−1115.7		1.88
3	−1113.8	58.62	
4	Plano		15121.
Surface	n_D	ν	Type
1	1.5209	60.22	ZK-2 (Schott)
3	1.5213	52.76	KzF-5 (Schott)

Remarks: This objective is essentially the same as the previous one and should be used if air-spacing is found to be necessary for the larger objectives. The design is coma-free and is somewhat better corrected spherically than the previous form. Nevertheless, some aspheric figuring will be necessary to complete spherical correction. Again, by figuring front and rear surfaces, one can eliminate chromatic spherical aberration.

KzF-5 glass type is given in the Schott catalog as very resistant to moisture but fairly sensitive to acid attack. As an internal element, the surfaces of KzF-5 probably will retain a clear polish. The comparatively low thermal coefficient of expansion means that nonreflection coatings can be applied with reasonable safety to quite large disks with consequent improvement in efficiency and resistance to weathering.

The objective under consideration has about the same residual color errors as those of the previous objective except for minor differences due to process of design. The chromatic residuals are:

Wavelength	Focal displacement	Semiapochromat (R.L.)	Standard achromat (R.L.)
4047 (h)	0.001876	19.5	46.4
4358 (g)	0.000785	7.6	21.1
4800 (F′)	0.000473	4.2	5.5
4861 (F)	0.000304	2.6	4.7
5461 (e)	0.000000	0.0	0.0
5876 (d)	−0.000146	−1.1	0.1
5893 (D)	−0.000130	−0.9	0.7
6438 (C′)	0.000037	0.2	2.8
6563 (C)	0.000186	1.2	3.5
7682 (A′)	0.000248	1.4	9.6

In any final design, of course, one could alter the residual color correction to favor either the deep red or the blue-green according to the nature of the problem to be solved. Once again it is evident that the residuals for d and D are caused by slight uncertainties in the catalog indices.

5. Cemented Semiapochromatic Triplet. Given here as a 51-cm $f/25$, but can be scaled to other focal lengths and clear apertures.

		Separations	
Surface	Radii (mm)	Glass (mm)	Air (mm)
1	6978.7	74.57	
2	−2818.9	43.16	
3	2034.0	67.62	
4	−61979.		12587.
Surface	n_D	ν	Type
1	1.5477	62.88	PSK-1 (Schott)
2	1.5578	53.84	KzFS-2 (Schott)
3	1.5477	62.88	PSK-1 (Schott)

Remarks: This objective in principle is a very good one. If the liquid cement described earlier can be made to work properly for larger objectives, one would have a very efficient planetary telescope indeed. The two air surfaces remaining in such an objective can be coated for nonreflection. At $f/25$ a cemented triplet eyepiece coated for nonreflection can be used with excellent results.

The thermal coefficient of expansion for PSK-1 is 6.9×10^{-6}. As given earlier, the coefficient for KzFS-2 is 5.3×10^{-6}. Thus, both glass types have relatively low expansion and are fairly well matched. By way of contrast, the BK-7 often used as a first element has a thermal coefficient of 8.2×10^{-6}, and F-4 has a coefficient of 8.6×10^{-6}.

The central thicknesses in this particular design have been adopted in anticipation of the use of liquid cement for the larger diameters. Smaller objectives can be redesigned with proportionately smaller thicknesses. If it becomes vital to employ air-spaces instead of cement, a redesign can allow for reduced thicknesses.

The chromatic residuals are:

Wavelength	Focal displacement	Semiapochromat (R.L.)	Standard achromat (R.L.)
4047 (h)	0.002118	26.5	55.7
4358 (g)	0.000949	11.0	25.3
4800 (F′)	0.000082	0.9	6.5
4861 (F)	0.000107	1.1	5.7
5461 (e)	0.000000	0.0	0.0
5876 (d)	0.000028	0.2	0.1
5893 (D)	0.000080	0.7	0.8
6438 (C′)	−0.000068	−0.5	3.4
6563 (C)	0.000048	0.4	4.2
7682 (A′)	0.000154	1.0	11.5

The above design is not complete until aspheric figuring has been accomplished to eliminate spherical aberration at $f/25$. With strictly spherical surfaces the rim ray at $f/25$ is overcorrected but only by about 0.4 Rayleigh limit, where the tolerance in this instance is computed on the basis of allowable rim ray displacement for spherical aberration.* If the aspheric figuring is carried out appropriately on both front and rear surfaces, it is possible to eliminate chromatic spherical aberration precisely. At $f/25$ the chromatic coma will in any case be small.

Unfortunately, PSK-1 is listed in the Schott catalog as one of the glasses subject to fine striation. Such a problem goes hand in hand with the low thermal coefficient of expansion. Table II indicates that this glass type is available in diameters up to about 70 cm for the scaled-up thicknesses adopted in the design. However, earlier data are much more conservative and indicate that only quite small disks are available in objective grade. If disks of objective grade can be obtained for both PSK-1 and KzFS-2 in sizes up to 15 cm, the objective might become useful for coronagraphic purposes.[28]

6. Air-Spaced Semiapochromatic Triplet. Given here as a 51-cm $f/14.76$, but can be scaled to other focal lengths and clear apertures.

		Separations	
Surface	Radii (mm)	Glass (mm)	Air (mm)
1	6397.2	80.01	
2	−788.2		8.00
3	−784.8	43.99	
4	828.1		8.00
5	860.7	72.01	
6	Plano		7393.9

Surface	n_D	ν	Type
1	1.5168	64.2	BK-7 (Schott)
3	1.5213	52.76	KzF-5 (Schott)
5	1.5890	53.16	BaLF-6 (Schott)

Remarks: This objective was designed for use in diameters up to 25 cm. For larger objectives the design should be modified for higher f/numbers, partially to alleviate the residual color aberration, and partially to minimize sensitivity to flexure and thermal gradients. Here, however, to be consistent it is necessary to consider the design as for a 51-cm $f/14.76$ which involves close Rayleigh tolerances. At $f/25$ the performance in terms of Rayleigh limits would be approximately three times improved. (Although these discussions frequently make use of Rayleigh limits for convenient comparisons, it must not be supposed that the Rayleigh limit of itself is sufficiently strict. See page 122 for the performance really demanded of an optimum planetary telescope.)

The chromatic residuals are:

Wavelength	Focal displacement	Triplet semiapochromat (R.L.)	Standard achromat (R.L.)
4047 (h)	0.001247	26.5	94.8
4358 (g)	0.000490	9.6	42.6
4800 (F′)	0.000022	0.4	11.1
4861 (F)	0.000178	3.2	9.7
5461 (e)	0.000022	0.3	0.0
5876 (d)	−0.000022	−0.3	0.2
5893 (D)	0.000468	5.5	1.1
6438 (C′)	0.000178	2.4	5.7
6563 (C)	0.000312	4.1	7.1
7682 (A′)	0.000223	2.5	19.6
10140	0.001069	9.1	51.3

The irregularities between F′ and F, and between d and D, are again the result of uncertainties in the catalog indices as exaggerated by the strong internal powers. Nevertheless, there is a marked improvement over the performance of the achromat, a fact that has been proved conclusively by the performance of several 12.5-cm objectives made up to the scaled formula. Indeed, a careful Hartmann measurement of the color curve of one of these objectives would offer a very good way of evaluating the relative indices of refraction to the sixth decimal place.

The objective is designed to be free of spherical aberration and coma. In addition, the objective is almost fully corrected for chromatic spherical aberration and chromatic coma. In very large diameters it will still be necessary to do some final figuring to produce a fine diffraction image in a mean wavelength, but the depth of figuring will be very small. If, instead, the f/number is increased, the need for figuring can be limited purely to compensation for any lack of homogeneity of the several glasses.

The color curve given above and indeed for all the preceding objectives has been calculated for the 0.707 zone of the aperture and therefore is representative of the actual diffraction performance of the objective. The paraxial values will be slightly different.

7. Cemented Apochromatic Triplet Objective with Fluorite with Aspheric Figuring. Given here as a 51-cm $f/10$ objective, but can be scaled to other focal lengths and clear apertures.

		Separations	
Surface	Radii (mm)	Glass (mm)	Air (mm)
1	2130.6	55.60	
2	1155.1	55.60	
3	−2521.3	55.60	
4	−9519.9		4973.

* See ref. 25 (Conrady), pp. 126–141.

Surface	n_D	ν	Type
1	1.5168	64.2	BK-7 (Schott)
2	1.4339	95.4	Fluorite (CaF_2)
3	1.5014	56.46	K-10 (Schott)

Remarks: The cemented fluorite objective given here can be manufactured only in diameters up to 15 cm or possibly to 20 cm. While one can obtain good polished surfaces on fluorite, there is a tendency for numerous pits and depressions to develop in an air-surface. It is safer to cement the fluorite between protective outer elements, whereafter the pits and depressions will become harmless. Liquid cement must be used because of the wide disparity between the thermal coefficient of expansion of fluorite (19.5×10^{-6}), BK-7 (8.2×10^{-6}), and K-10 (6.8×10^{-6}).

The first model of the above fluorite apochromatic triplet was designed and built in 1943 with the first synthetic fluorite available from the MIT wartime crystal laboratory. The design was slightly modified and improved in 1955. Every effort was made in the redesign to produce essentially a completely corrected fluorite triplet, corrected not only for secondary spectrum, but also for spherical aberration and coma, and for chromatic spherical aberration and chromatic coma. It will be of interest to reproduce here the table of values that resulted from computations for the 15-cm $f/10$ intended to be manufactured in 1955. Unfortunately, because of budgetary restrictions the actual prototype was made as a 7.5-cm system.

Table VII. Transverse Intercepts in the Gaussian Focal Plane for a 15-cm $f/10$ Fluorite Triplet (with Aspheric Figuring)

Wavelength Zone	g	F	e	C	A′
0.000	0.000	0.000	0.000	0.000	0.000 mm
0.200			0.000		
0.400			0.000		
0.533			−0.001		
0.667	−0.001	−0.001	−0.001	0.000	−0.008
0.800	0.000	−0.001	0.000	0.000	−0.010
0.933	−0.001	−0.001	0.000	0.001	−0.010
1.000	0.000	−0.001	0.000	0.002	−0.010

The above tabulation is necessarily in terms of geometrical optics, and being in the form of transverse intercepts yields the radius of the image error. At $f/10$ the Rayleigh tolerance transversely would be of the order of 20 wavelengths of the given color. For green light the transverse tolerance would be approximately 0.010 mm. The fluorite objective is therefore corrected to a small fraction of a Rayleigh limit for the gamut of wavelengths down nearly to A′ in the deep red.

The full design, as determined in 1955, includes aspheric figuring of the respective surfaces and requires the closest attention from a skilled optician. At $f/15$ or $f/20$ the modified design would require little or no figuring.

One should not use a fluorite objective for any application requiring thermal stability of focal setting unless an insulated or thermostated cell sufficient for the purpose can be designed. The change of focus with change of temperature is quite pronounced. Such an objective would never do for astrometric work. For visual use as a planetary telescope in apertures up to 20 cm, however, at $f/10$ or $f/20$ the fluorite objective would be excellent.

The chromatic residuals for the 51-cm $f/10$ are:

Wavelength	Focal displacement	Fluorite apochromat (R.L.)	Standard achromat (R.L.)
4047 (h)	0.000129	4.0	139.2
4358 (g)	−0.000106	−3.1	64.0
4861 (F)	−0.000058	−1.5	14.3
5461 (e)	0.000000	0.0	0.0
5893 (D)	0.000112	2.4	2.0
6563 (C)	0.000004	0.1	10.4
7682 (A′)	−0.000144	−2.4	29.0

The above tabulation has been included purely for sake of comparison. One should note how poor the standard achromat becomes for so large an $f/10$ system. One would never build a 51-cm $f/10$ fluorite objective, even if the fluorite disk could ever be made. A 51-cm $f/20$ would have errors only one-fourth as large and would be parfocal within the Rayleigh limit over a wide spectral range.

The above discussion with examples must be regarded as quite incomplete in view of the availability of many dozens of glass types that might well be used in apochromatic combinations, and in view of the multiple-element systems that are feasible for various purposes other than planetary telescopes. Even with respect to planetary telescopes one can find many triplet combinations that will be of quality similar to the few examples given here. Some will have even more apochromatic color curves than in the examples, but the author has tried to keep internal lens powers to reasonable values.

Many of the glass types that might be useful as positive elements cannot be obtained in full objective quality at present, owing to the presence of fine striation. Such unusual types as K-11, PSK-1, PSK-2, ZK-7, PSKS-1, and PKS-1 are among these. However, it is certain that the minor amount of light energy lost from the beam or scattered into the diffraction rings from the central core of the image because of fine striation becomes relatively insignificant compared to the degrading influence of the slightly defocused light

energy arising from the disturbing effect of secondary spectrum.

It would not be advisable at this time to determine just what the most practical combination of glass types and design parameters would be in coming as close as possible to the idealized planetary telescope with performance as good as the criterion adopted on page 122 above. It would be possible to attempt it on the basis of information at hand, but a better way would involve a cooperative venture in which the glass manufacturers play an equal role with the designer. In such an effort the budget should be large enough to allow for a great deal of experimental development and trial production of large disks.

It is a serious question whether a project involving the building of a large apochromatic planetary telescope of the size perhaps of the Lick 91 cm would be worthwhile in modern scientific terms. If the instrument existed, certainly it would be a pleasure to use, and much good scientific work could be accomplished with its use. However, in the light of researches soon to take place with balloon-borne telescopes and orbiting astronomical observatories, not to mention actual instrumented payloads sent to the near vicinity of Mars and Venus, one would have to be very cautious. It may be that improved apochromatic instruments of intermediate size will be worthwhile for combined scientific, instructional, and public purposes, but perhaps the time has passed when a truly fine, large apochromatic refractor would have had an important role to play.

Even if the answer should be negative, there are still many important astrometric problems to be solved by means of ground-based telescopes.[29] Some of these telescopes will continue to be of the refracting type and in improved form may involve multiple-element semiapochromatic or fully apochromatic systems possibly of the Herzberger degree of perfection. Careful attention must also be given to the possibilities newly created by the work of Schroeder.[30]

In conclusion the author should like to repeat that the great advances made in the technology of optical glass have now made it feasible to manufacture semiapochromats, full apochromats, and Herzberger Superapochromats*, in quite large diameters. An appreciable gain in visual perception should result from their use. The fabrication of a successful large semiapochromat or full apochromat requires that the closest attention be paid to all phases of the work by engineers and opticians of the highest skill and particularly that the glass manufacturers be allowed adequate time and budget to complete effectively their own most important portion of the endeavor.

* A Superapochromat is superachromatically corrected over the full aperture for aplanation.

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Papers to appear in subsequent issues

We have had so many papers submitted for publication during the past year that we have already built up a backlog which is as embarrassing for a new publication as it is a demonstration of the need for this journal. We have done our best to publish papers as quickly as we can by bringing out bigger issues than had originally been intended last year, **becoming a monthly in 1963** and by temporarily dropping some of the "filler" departments. The Editors wish to express their sincere appreciation to all contributors who have thus demonstrated their faith in *Applied Optics*.

Infrared Transmission through the Atmosphere—*Green and Griggs*
Performance Prediction of Range-Finder Systems—*Patrick*
Three-Dimensional Wavefront Reconstruction—*Meyer-Arendt*
Experimental Transfer Characteristics of Image Motion and Air Conditions in Aerial Photography—*Hendeberg and Welander*
Method of Inferring Single-Path Band Transmission Factors from Double-Path Measurements—*McKiernan and Wessely*
Thermal Radiation from a Hemispherical Source in Contact with an Infinite Plane—*Kester and Minardi*
Total Absorptance of Water Vapor in the Near Infrared—*Burch et al.*
Isocon Scan—A Low-Noise Wide-Dynamic-Range Camera-Tube Scanning Technique—*Cope and Borkan*
Design Theory for a Submersible Scattering Meter—*Tyler*
A Simple Grating Calibrator for the Visible and Vacuum Ultraviolet—*Hammer, Arakawa, and Birkhoff*
Comparison of AM and FM Reticle Systems—*Carpenter*
Modifications of a Beckman Spectrophotometer for Direct Measurements of Spectral Energy Distribution of Light Sources—*Grum*
Production and Use of Variable-Transmittance Sinusoidal Test Objects—*Lamberts*
A Simple Voltage Amplifier for Photovoltaic Cells—*Paix*
Generation of Sinusoidal Light Intensity—*Julich*
An Automatic Rapid-Scanning Spectrophotometer to Study Thermoluminescence Spectra—*Ghosh*
Use of a Kaleidoscope to Obtain Uniform Flux over a Large Area in a Solar or Arc Imaging Furnace—*Chen et al.*
Photorefractometer I. Extension of Sensitivity and Range; II. Measurement of N and K—*Kapany and Pontarelli*
Faraday Rotation in FeNi Films—*Wieder and Collins*
Photographic Emulsions as Computer Storage Media—*Levi*
Lighting Parameters and Generalized Characteristics of Xenon Lamps—*Marshak*
Design of Superachromatic Lenses—*Herzberger and McClure*
Reflection and Transmission of Infrared Materials—*McCarthy*
Multilayer Reflection Coatings on a Metal Mirror—*Young*
Interferometer Laser Mode Selector—*Collins and White*
Enhancement in Mercury-Krypton and Xenon-Krypton Gaseous Discharges—*Grosof and Targ*
The Use of Polarized Infrared Radiation in Magneto-optical Studies of Semiconductors—*Palik*
A Multicolor Photoelectric Photometer for Artificial Satellite Observations—*Moore and Elliott*
A Method for Evaluating Laser Potentialities of Crystals—*Theissing et al.*
Focusing of Light by a Dielectric Rod—*McKenna*
Some New Aspects for Laser Communications—*Megla*
A Density Recording Vacuum UV Spectrophotometer—*Onaka and Ejiri*
An 8–14 μ IR Astronomical Photometer—*Westphal and Murray*
An Optical Null Double-Beam Double-Pass IR Spectrophotometer—*Minami*
A Photomultiplier Circuit for Precision Spectrophotometry—*Budde*
Large Scale Photoelectric Planimeter for Leaves—*Carman*
Spectral Band Absorptance for Atmospheric Slant Paths—*Plass*
A New Method for High-Speed Motion Picture Photography of Transparent Drops—*Pfeiffer*
Photometric Accuracy of Infrared Spectrophotometers—*Stewart*
Absorption by Ozone in the 4.75-μ Region of the Solar Spectrum—*McCaa and Shaw*
Exploding Wire Blast Shutter—*Chace and Fish*
Laser Operation at 3.39 μ in a Helium-Neon Mixture—*Bloom et al.*
A New Type of Shearing Interferometer for the Measurement of Transfer Functions of Microscope Objective—*Tsuruta*
The 15–26 μ Sky Emission Spectrum at the Jungfraujoch (3570 m)—*Bolle*
Measurements and Interpretation of Laser Beam Divergence—*Evtuhov and Neeland*
Infrared Dispersion of Some Oxide Glasses—*Malitson et al.*
Study of the Fabrication of Aspherical Surface—*Sakurai and Shishido*
Theory of Optical Information Storage in Solids—*van Heerden*
A New Optical Method of Storing and Retrieving Information—*van Heerden*
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Milestones in Optics II—Thomas Young—*Barr*
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High-Index-of-Refraction Spherical Sheath Composite-Rod Optical Masers—*Svelto and Di Domenico*
Interferometric Method of Velocity of Light Measurements—*Stroke*
Brighter Spectrographic Images by the Use of Anamorphic Optics—*Eisner*
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Quantum Limit to Precision of Wavelength Determination—*Hanes*
Improved Silver Films for Multiple-Beam Interferometry—*Bradley*
Rapid Measurement of Photographic Records of Interference Fringes—*Dyson*
Empirical Methods for Computing the Integrated Absorptances of Infrared Bands of Atmospheric Gases at Nonuniform Pressures—*Shaw*
Interference Comparators for Line Standards—*Baird*
Use of an Analog Computer in Side-on Arc Spectroscopy—*Shumaker and Yokley*

Reduction of Scattered Light in the Coronagraph

Gordon Newkirk, Jr., and David Bohlin

The development of balloon and rocket vehicles provides opportunity for nearly continuous observation of those parts of the solar corona remote from the sun. This opportunity places new requirements on the freedom of the coronagraph from scattered light. Several possible means of improving the coronagraph are described. It is found that the available optical media do not permit a significant reduction in the scattered light in the ordinary coronagraph. The reflecting coronagraph and the simple, externally occulted coronagraph can be made freer of scattered light by from one to more than two orders of magnitude, respectively, than the Lyot coronagraph. The use of the apodized, external, occulting disk developed by several investigators can reduce the scattered light by at least three orders of magnitude so that the instrumental background is similar to the skylight encountered during total eclipse.

Introduction

Until the development of the coronagraph by Lyot[1-3] three decades ago, the solar corona was visible for only a few minutes every year during total eclipse. As was demonstrated during the International Geophysical Year,[4] the several Lyot coronagraphs placed on mountaintops around the world were able to provide a reasonably continuous record of the emission line corona within the first 100,000 km (0.1 solar radius) of the solar limb. However, the relation of the outer corona (Fig. 1) to the more easily observable inner part is still unclear. If the corona and its connection with the interplanetary medium are to be understood, the region of frequent observation must be extended to several solar radii. At present, occasional images of the corona to one solar radius above the limb have been built up by scanning with the K-coronameter.[5-10] Except for the analysis of occasional occultations of radio stars, the study of radio noise of coronal origin, and the infrequent penetration of space probes, the structure of the outer corona is still unknown outside of eclipse.

Ideally, frequent, high-resolution pictures of the corona should be made during a period of several weeks or months. It would then be possible to study not only such short-lived, transient changes in the corona as may follow solar flares, but also the more gradual changes which accompany the formation and decay of the solar active regions. By placing an improved version of the coronagraph above the atmosphere in either a balloon or an orbiting solar observatory, we can hope to realize the long sought for opportunity of nearly continuous observation. Moreover, improved coronagraphs will assist in the solution of planetary atmosphere problems, in the search for planets accompanying nearby stars, or in any other experiment in which a faint source must be distinguished from a close, bright one.

It is valuable to examine the freedom from scattered light that is required of any coronagraph used above the atmosphere. The Lyot coronagraph, although it allows a reduction of the scattered light by at least a factor of 100 below that contributed by the best of simple telescopes, still scatters light of radiance approximately 5×10^{-6} that of the mean solar disk. Since the radiance of the sky seen from high mountaintops on the clearest days[3,11,12] is approximately 10^{-5} in the green, the Lyot coronagraph is completely adequate for use at any ground-based observatory. At such stations only the inner corona with a radiance of the order of 10^{-6} is accessible to direct observation. Since the corona can be photographed directly only when it has a radiance at least 10% in excess of the background, examination of the corona to six solar radii requires reduction of the background to approximately 10^{-9}. This lower level of scattering is a realistic goal for the improvement of the coronagraph.

The performance of the satellite-borne coronagraph

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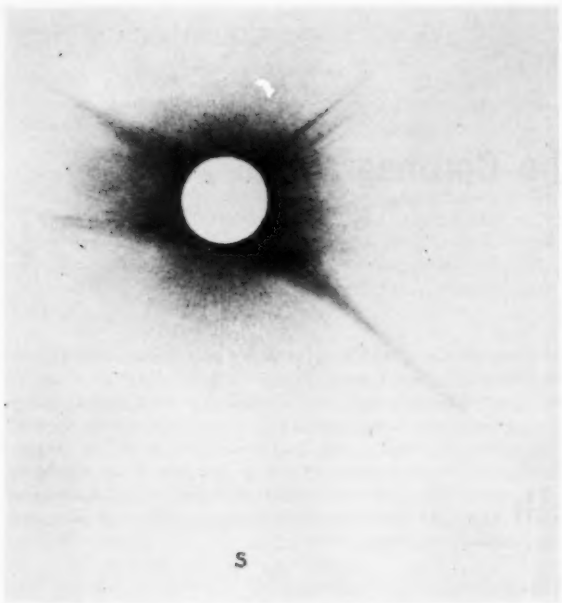


Fig. 1. The solar corona as depicted in an original drawing by the late Mr. Wesley, Secretary of the Royal Astronomical Society. The drawing was made from the negative of a photograph made by Mrs. Annie S. Maunder, who photographed the 22 January 1898 eclipse at Talni, Hyderabad on a Sandall triple-coated plate. The connection between the outer coronal streamers, which extended to an unusual distance in 1898, and active regions on the surface of the sun as well as magnetic storms on the earth remains a challenging mystery of solar physics.

is limited only by scattering within the instrument. The balloon-borne instrument can, in practice, be placed above only about 99% of the atmosphere, and it is necessary to examine the character of the skylight at high altitudes more closely. Measurement at altitudes of up to 25,000 m at wavelengths from 0.4 μ to 0.8 μ show a sky radiance of the order of 10^{-8} that of the mean solar disk.[13] Comparison of the corona and the sky at 25,000 m, as in Fig. 2, suggests that at $\lambda = 1.2\ \mu$ the corona should be visible to approximately four solar radii. To detect the corona at the desired six solar radii the sky background must be reduced by a factor of three by carrying out the observations at an altitude of 33,000 m.

Before describing the techniques by which the scattered light in the coronagraph can be reduced to a radiance of the order of 10^{-9} that of the disk of the sun, a value that is only slightly above the sky encountered during a solar eclipse,[14] we shall review the scattering produced in the traditional Lyot coronagraph.

Sources of Scattering in the Lyot Coronagraph

In his patient analysis of the scattering by a simple objective lens Lyot distinguished five sources of stray light which can all be seen clearly in a lens illuminated by a synthetic sun (Fig. 3). As in the coronagraph the "solar image" is occulted by a disk, and the lens is viewed in the stray light which passes the disk. The sources of scattered light are:

1. Diffraction at the aperture of the objective lens. If unobstructed, this diffraction ring produces a radiance in the field of the coronagraph of approximately 2×10^{-4} of the mean solar radiance $B_\odot$.

2. A spurious solar image produced by multiple reflections in the objective lens. This image is about $^1/_6$ of the focal length away from the objective and introduces stray light of radiance

$$B \approx 6 \times 10^{-9} (f/D)^2 B_\odot,$$

where f is the focal length of the objective and D its diameter. In Fig. 3 the central bright spot is slightly out of focus.

3. Macroscopic inhomogeneities in the glass. Small bubbles and inclusions produce many of the randomly distributed starlike spots in Fig. 3.

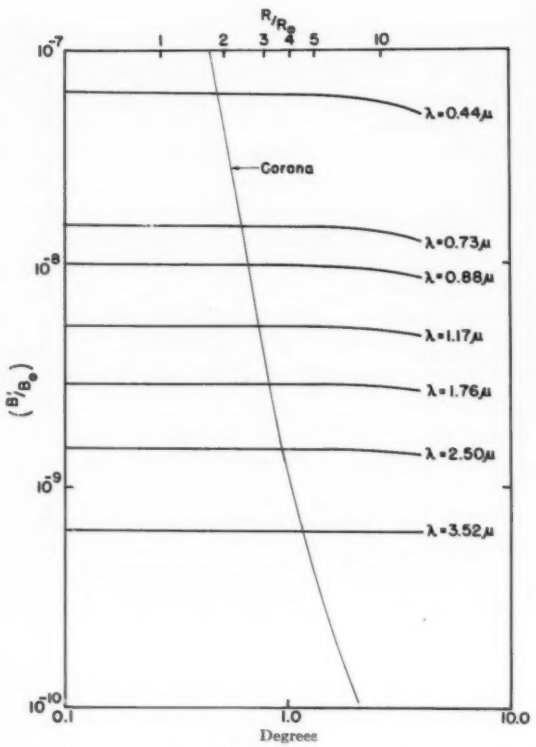


Fig. 2. A comparison of the radiance of the sky at 25,000 meters and of the solar continuum corona at several wavelengths. The radiances from 0.44 μ to 0.8 μ were measured[13] while the values at longer wavelengths were inferred from the size distribution of the particles determined by means of the angular distribution of scattered light at visible wavelengths. Coronal radiances are plotted as a function of the distance from the center of the solar disk in units of the solar radius $R_\odot$.

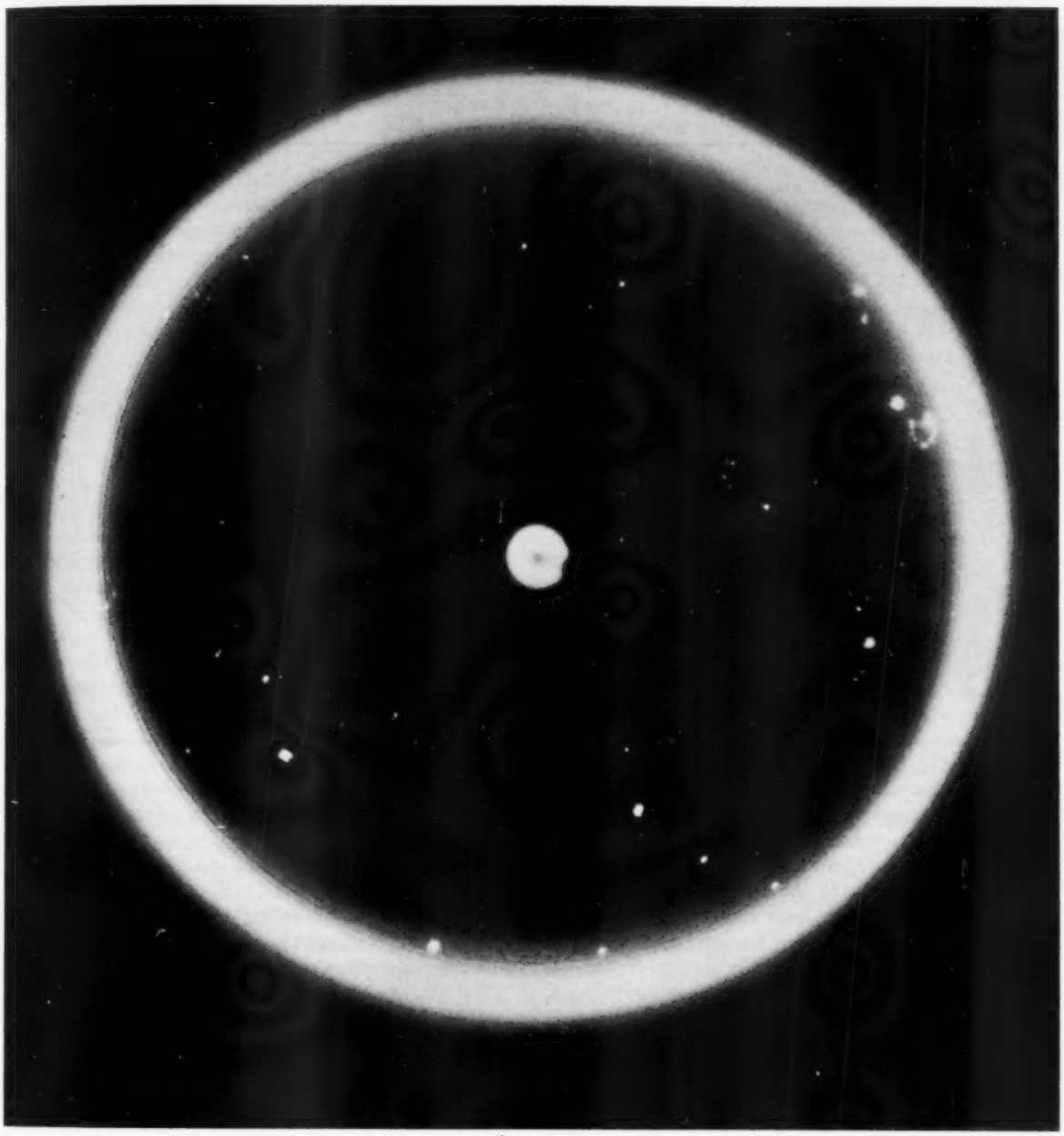


Fig. 3. Photograph of a coronagraph lens illuminated by a laboratory source of 32 min of arc diameter. This particular lens produced stray light of radiance 3.3×10^{-6} that of the mean solar disk.

4. Departures of the surface of the lens from a uniform shape. Pits in the surface of the glass produce starlike images very similar to the bubbles within the glass. Also as departures of the surface from ideal shape we must include scratches on the glass and any other lack of perfection in polish or figure as well as dust residing temporarily on the surface.

5. Body-scattering within the glass itself. This source produces an apparently uniform haze over the entire aperture. We here distinguish between the macroscopic inhomogeneities in the glass, such as large bubbles and striations (source 3), and microscopic inhomogeneities.

Lyot found that by using a field lens to image the objective on an aperture which did not pass the bright diffraction ring and by eliminating the multiple re-

Table I. Comparison of Scattering by Sample Coronagraph Lenses

Glass type	Sample no.	Manufacturer	Striae	Granulation	Surface	Bubbles	Fluorescence	$B/B_\odot$ (10^{-6}) for $\lambda = 0.54\ \mu$
Samples free of obvious surface defects and striae								
BSC-2	3	Corning	Absent	Weak	Good	Very few	Faint yellow	1.2
Fused silica (Schlieren grade)	3	Corning	Absent	Weak	Good	Very few	—	1.7
BK-7	2	Schott	Absent	Medium	Good	Few	—	2.4
BK-7	1	Schott	Absent	Medium	Good	Few	—	2.5
Ultrasil	2	Engelhard	Absent	Medium-strong	Good	Few	—	2.5
PK-2	1	Schott	Absent	Medium	Good	Few	—	3.3
Fused silica (Schlieren grade)	1	Corning	Absent	Weak	Pits?	Several	—	4.2
Ca F_2	1	Harshaw	Absent	Severe	Sleeks?	Medium	Strong blue	21
Samples with defects								
BSC-2	1	Corning	Wide-band	Medium	Good	Few	Faint yellow	2.8
Ultrasil	1	Engelhard	Absent	Medium-strong	Scratch	Few	—	3.1
BSC-2	2	Corning	Band	Medium	Good	Few	Faint yellow	3.4
BK-7	3	Schott	Absent	?	Poor polish	Few	—	5.6
LF-4	1	Schott	Absent	Medium	Faint scratch	Several	Faint blue	5.7
Ba-SFS-1	1	Schott	Absent	?	Etched by cleaning in water	?	Strong yellow	33

flection spot by placing a small occulter on the center of the second objective lens he was able to reduce the stray light in the coronagraph to about 5×10^{-6}. He concluded that most of the residual illumination is due to the scattering by the inevitable bubbles and inclusions and by the body-scatter of the glass. Since the technology of glassmaking has advanced considerably in the intervening 30 years, it appears fruitful to seek an optical medium that can be fashioned into a coronagraph lens with considerably less scattering.

Scattering in Various Optical Media

It must be remembered that forward scattering by the imperfections of the objective lens is of great importance in the coronagraph. Thus, scattering by large bubbles and by irregularities of microscopic (0.5 μ to 100 μ) dimensions completely dominates that from any irregularities of atomic (1 Å to 10 Å) scale. This fact is emphasized by the observation that objective-lens scattering is many orders of magnitude higher than one would expect from the random density fluctuations inherent in the glass.[15]

With this information in mind we can place some very general requirements on the medium for a coronagraph lens in approximately the following order of importance:

1. Absence of striations, bubbles, and inclusions.
2. Ability to take a fine polish and to resist scratches during cleaning (hardness).
3. Absence of fluorescence in the spectral region of interest.
4. Resistance to etching by water, the common solvents, and various air-borne pollutants likely to be encountered during use.
5. Absence of birefringence.

These requirements suggest the use of several of the colorless, cubic crystals such as cristobalite, spinel, and diamond, which are hard enough to resist scratching. Unfortunately, large optical quality samples of these minerals are rare. Such minerals as fluorite (CaF_2), barium fluoride, and lithium fluoride, which can be obtained as large synthetic crystals of optical quality, are so soft that they are, in our experience, nearly impossible to polish to coronagraph quality.

We have tested several samples of modern glasses by using each one as the objective (2.5 cm diameter; 25 cm focal length) of a small, laboratory coronagraph. Radiation from the entire coronagraph field of diameter of approximately eight solar radii was recorded by a photomultiplier, which was calibrated by a series of opal glasses of known surface radiance placed before the objective. Comparison between independent measure-

ments indicates that the scattering from a particular sample is accurate to about 10%.

The results of these measurements appear in Table I in which the various lens samples are listed in order of their excellence. Since the varieties of glass were chosen for absence of bubbles, it is not surprising that only a few of the samples show a large amount of scattering. However, all the samples had some body-scattering in the form of a "granular structure." The fact that those lenses with the weakest granulation also scattered the least amount of light indicates that this structure contributes significantly to the scattering by the lens. Under high magnification the granular structure in the glasses and the fused silica can be recognized as a regime of minute bubbles which seem to be merely the lower size range of the spectrum of bubble sizes. The less frequent but larger bubbles can, of course, be recognized as individuals. Granulation in the fluorite sample, however, was of an entirely different character and appeared as a cellular structure distributed throughout the volume of the crystal.

Examination of Table I also shows that faint scratches and striae can add approximately $1\text{–}2 \times 10^{-6}$ per scratch to the scattering. *One concludes that carefully selected blanks of the common crown glasses BSC-2 or BK-7 as well as the best grades of fused quartz make the best coronagraph objectives so far as scattering is concerned.* Although the LF-4 lens scatters significantly more than the best samples, it does not seem to deserve the bad reputation for high scattering usually associated with flint glass and could doubtless be used as a component in an achromatic coronagraph lens suitable for ground-based observation.

Although these optical media are transparent in the visible region, several of them absorb rather strongly at short wavelengths. Unfortunately, energy absorbed at short wavelengths may reappear in the form of fluorescence and contribute a significant amount to the stray light in the coronagraph field. This is illustrated by the case of diamond—apparently an otherwise suitable medium for coronagraph lenses—which when irradiated by light of wavelength shorter than 2600 Å fluoresces in the blue or in the green.[16] Several of the lens samples tested for scattering also exhibit fluorescence in the visible (Table I). The glasses containing somewhat loosely bound ions of boron, barium, and lead, within the SiO_2 network of the glass have strong absorption in the 2000 to 3000 Å region and show the strongest fluorescence.[17] Although we have made no comparison on an absolute intensity basis, the fluorescence of BSC-2 glass suggests that this otherwise excellent lens medium should not be used in a coronagraph operated completely above the atmosphere where the ambient, ultraviolet flux is extremely high. In fact, even fused quartz fluoresces under exposure to sufficiently short wavelength radiation. The design of a satellite-borne coronagraph should be made with the possible hazard of fluorescence in mind. A coronagraph at balloon altitudes is protected from radiation short of 3000 Å by the overlying ozone absorption, and the selection of a lens free from fluorescence is correspondingly easier.

Reflecting Coronagraphs

One concludes from the preceding section that minute bubbles within even the best glasses prevent the construction of coronagraph lenses of close to theoretical performance so far as light scattering is concerned. In the reflection coronagraph the pinholes, minute hills, and granular structure that appear in metals deposited on glass scatter more radiation than the imperfections within the glass of the ordinary system.[18] Until new techniques of depositing completely uniform coatings of metal on glass or of producing polishable metals of high quality are developed to a sufficient standard of excellence, the uncoated mirror offers a useful alternative. The mirror coronagraph with uncoated primary surface takes advantage of the excellent polish which can be given to such media as glass or quartz as well as the fortunate circumstance that the bubbles in the medium scatter principally in the forward direction. Our tests of the scattering from a sample of fused quartz show that the advantage of low backscatter more than compensates for the disadvantage of the small reflectivity of the primary surface. The scattered light in such a coronagraph should be at least an order of magnitude smaller than in the objective lens coronagraph. We are presently investigating the practicality of such a reflecting system.

Disposal of the unwanted radiation passing through the primary surface can, of course, be a problem. The use of an opaque glass or an antihalation coating on the back surface is likely to heat the mirror excessively and cause distortion of its figure. However, very simple schemes, such as shown in Fig. 4, allow most of the radiation to pass through the mirror to a light trap while only 4% of the incoming flux must be absorbed

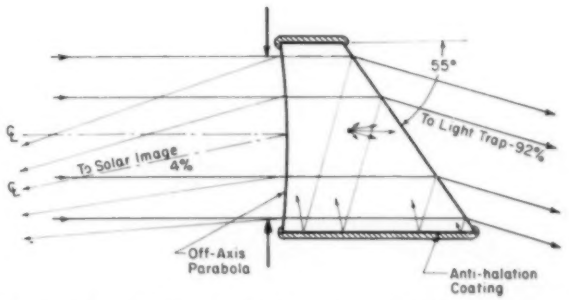


Fig. 4. The mirror for a reflection coronagraph in which stray reflections are greatly reduced.

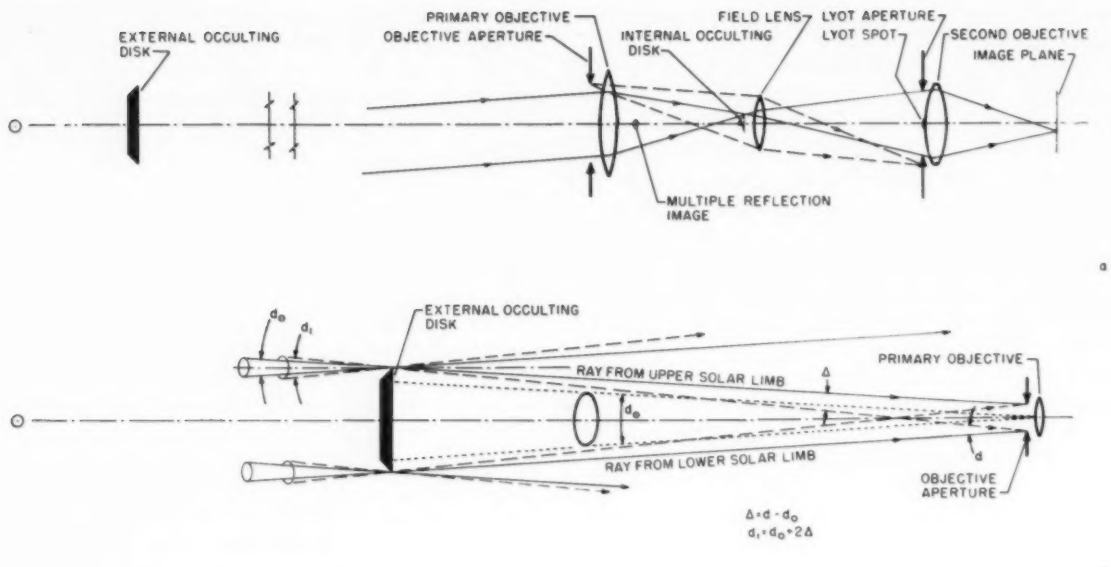


Fig. 5. (a) Schematic diagram of the externally occulted coronagraph. The occulting disk prevents direct photospheric light from falling on the primary objective lens while a second disk blocks the bright diffraction image of the first occulting disk. Light diffracted at the objective aperture is brought to a focus on the Lyot aperture by the field lens. A small spot in the center of the second objective blocks the multiple reflection image of the external occulting disk. (b) Geometry of the external occulting. The angular diameter d of the occulting disk must exceed that of the sun by Δ.

in the antihalation coating. The high efficiency of antihalation layers with the same refractive index as that of the mirror (e.g., Luxorb)[19] allows the stray light within the mirror to be reduced to from 4×10^{-6} to 4×10^{-7} of the incoming intensity after one reflection from a treated face. Reflection off a second treated face reduces this quantity by another factor of from 10^{-4} to 10^{-5}.

Externally Occulted Coronagraphs

Although the previous two sections suggest that the scattered light in the coronagraph can be substantially reduced, we must conclude that, at the present time, the necessary several orders of magnitude improvement over the Lyot coronagraph required of the satellite or balloon-borne systems can only be accomplished by shielding the objective lens from direct photospheric radiation. The most practical means of doing this is with an external occulting disk.

The first to suggest a coronagraph with an external occulting disk was John W. Evans.[20] A sky photometer based on Evans' design was used by one of us[12] to study the solar aureole from various mountain peaks. A modification of this externally occulted coronagraph has been flown to altitudes of 25,000 m[13,21] to determine the variation of sky radiance with angle from the sun, wavelength, and altitude.

The nature of the externally occulted coronagraph (Fig. 5a) requires that d, the angular diameter of the occulting disk as seen from the objective, exceed that of the sun, $d_\odot$, by an amount, Δ, which is just the angular diameter of the objective lens as seen from the occulting disk. The reason for this requirement is clear from Fig. 5b. The fact that the corona within the diameter d_1 is vignetted may be used in some cases partially to compensate the sharp decrease of coronal radiance with increasing distance above the solar limb. The advantage of having the occulting disk supported far in front of the objective lens is that the corona can be examined close to the solar limb. However, the impracticality of using an external occulting disk on a ground-based coronagraph of, say 15 cm aperture, can be seen from the fact that the disk must be 262 m away from the objective if the corona is to be examined as close as two minutes of arc of the limb.

Measurement shows that the stray light in an externally occulted coronagraph is about 10^{-8} of the mean solar disk. Although this represents an improvement factor of approximately 500 over the Lyot coronagraph, it is still an order of magnitude too large for meaningful coronal photography above the atmosphere. The major source of this residual stray light is diffraction by the occulting disk.

One obvious method of decreasing the scattered light in the externally occulted coronagraph is to increase the size of the occulting disk without correspondingly increasing the diameter of the objective lens. That such occulting does reduce the flux onto the objective

lens is shown in Fig. 6. Such a device is rather impractical since the occulting disk also blocks most of the corona. A more subtle artifice is to apodize the occulting disk.

The technique of apodization[22,23] can be used to modify the diffraction pattern about the Gaussian image point of a lens by a suitable variation of the transmission across the lens. The same technique, under the name of "antenna tapering," has been used by radio engineers to suppress the side lobes of the patterns of radio interferometers. The aperture stop at the second objective of the Lyot coronagraph produces, in a very real sense, an apodization of the objective lens in which resolution is sacrificed for a dramatic decrease in the diffraction far from the Gaussian image point. An analogous problem is that of the apodization of the occulting disk except that the conditions of Fresnel rather than Fraunhofer diffraction apply. Here one desires to reduce the light diffracted by the external occulting disk into the aperture of the objective lens by a suitable "tapering" of the disk outside the limb of the sun.

A point source illuminating a disk produces a bright spot in the center of the shadow. This bright spot is seen in Fig. 7. If a means can be found to eliminate the central spot behind the occulting disk, the major source of stray light in the externally occulted coronagraph can be removed.

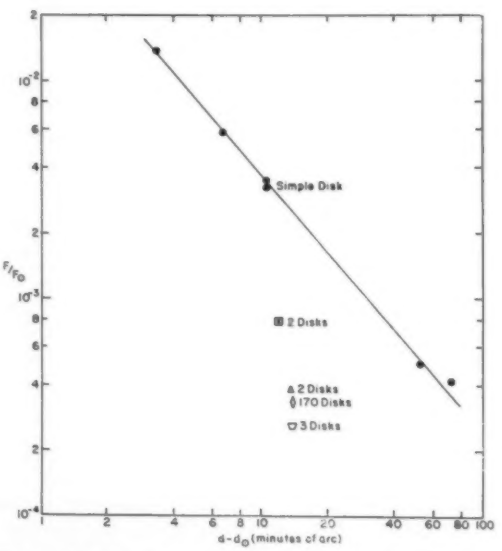


Fig. 6. Reduction of the flux into an objective aperture 1.2-mm diameter placed 76 cm behind various occulting disks. Here F is the flux observed with the occulting disk in place, while $F_\odot$ is the flux in the unobstructed beam. The reduction is plotted as a function of the difference between the diameter of the occulting disk and the diameter of the sun in min of arc. The synthetic sun was a ribbon filament lamp whose objective lens subtended an angle of 32 min of arc from the objective aperture.

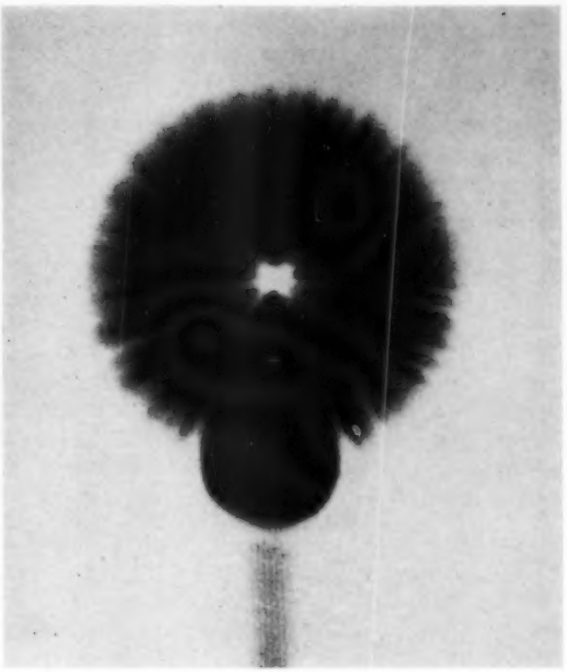


Fig. 7. The distribution of light in the shadow of a circular occulting disk illuminated by a point source. The familiar, bright, central spot is predicted by the Fresnel diffraction theory. The radial lines are caused by minute irregularities in the edge of the occulting disk.

To see that the bright, central spot can be removed in principle, consider the amplitude at the point P illuminated by a point source P_0. By the Fresnel theory the amplitude at P is[24]

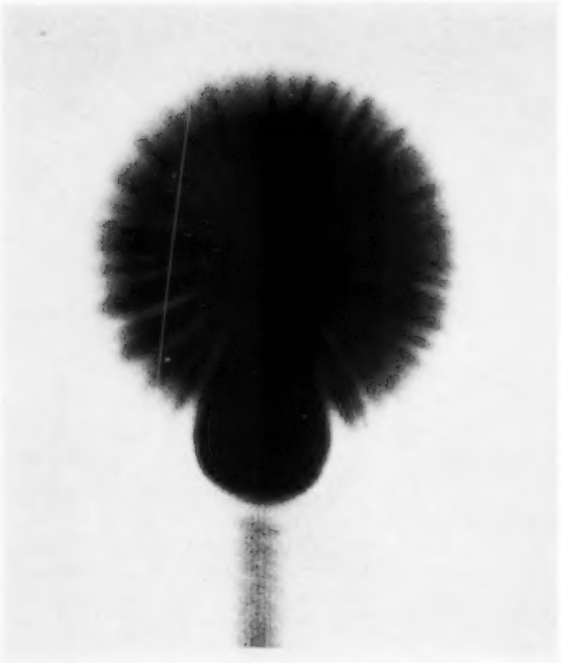
$$U(\mathrm{P}) = 2i\lambda \frac{Ae^{ik(r_0+b)}}{r_0+b} \sum_{l=1}^{n} (-1)^{l+1} \kappa_l, \qquad (1)$$

where

A = amplitude of the incident wave at unit distance from the source,
r_0 = radius of the wave front from P_0,
b = distance from P to the nearest point of the wave front,
k = $2\pi/\lambda$,
κ_l = the inclination factor that describes the variation of amplitude of the secondary wavelets with angle of diffraction χ.

The usual development makes use of the fact that κ is a smoothly decreasing function of χ and tends to zero as $\chi \to \pi/2$, $(l \to n)$. If a circular obstruction covers the first $j-1$ Fresnel zones, the summation in (1) is written

$$(-1)^{j+1} \sum_{l=j}^{n} (-1)^{l+1} \kappa_l = \frac{\kappa_j}{2} + \left(\frac{\kappa_j}{2} - \kappa_{j+1} + \frac{\kappa_{j+2}}{2}\right) + \left(\frac{\kappa_{j+2}}{2} - \kappa_{j+3} + \frac{\kappa_{j+4}}{2}\right) + \ldots. \qquad (2)$$



(a)

(b)

Fig. 8. The distribution of light in the shadow of a multiple occulting disk (a) and a toothed wheel (b) illuminated by a point source. The disappearance of the bright central spot is obvious. The multiple occulting disk was calculated so that the objective aperture would be completely contained in the central dark region of the shadow.

Following the argument, we note that the terms in parentheses are vanishingly small since

$$\kappa_n \approx \kappa_{n+1}$$

and

$$(-1)^{j+1} \sum_{l=j}^{n} (-1)^{l+1} \kappa_l \approx \frac{\kappa_j}{2}, \tag{3}$$

a classical result.

Consider, now, that although the first $j-1$ zones are blocked, the zones from j to m are not completely clear but obscured by an apodization factor a_l. Corresponding to Eq. (2) we have

$$\begin{aligned}(-1)^{j+1} \sum_{l=j}^{m} (-1)^{l+1} \kappa_l = {} & \frac{\kappa_j a_j}{2} \\ & + \left(\frac{\kappa_j a_j}{2} - \kappa_{j+1} a_{j+1} + \frac{\kappa_{j+2}\, a_{j+2}}{2} \right) + \cdots \\ & + \left(\frac{\kappa_{m-2}\, a_{m-2}}{2} - \kappa_{m-1}\, a_{m-1} + \frac{\kappa_m a_m}{2} \right) \\ & + \left(\frac{\kappa_m a_m}{2} - \kappa_{m+1} + \frac{\kappa_{m+2}}{2} \right) \\ & + \left(\frac{\kappa_{m+2}}{2} - \kappa_{m+3} + \frac{\kappa_{m+4}}{2} \right) + \ldots, \end{aligned} \tag{4}$$

if $m - j$ is even. To retain the feature of the ordinary Fresnel diffraction theory we need only require that $a_l \approx a_{l+1}$ and $a_m \approx 1$. The usual argument concerning the vanishing of the bracketed terms still applies and

$$(-1)^{j+1} \sum_{l=j}^{n} (-1)^{l+1} \kappa_l \approx \frac{\kappa_j a_j}{2}.$$

A similar result holds for odd $m-j$.

Thus, the intensity at P is reduced by the factor a_j^2, which, in principle, can be made arbitrarily small, *and the central, bright spot (Fig. 7) can be substantially reduced in intensity.* Although the illuminating source for a practical coronagraph has a finite solid angle, the problem is essentially the same with each point of the solar disk acting as a coherent source.

Several means of producing the apodization have been suggested. An ingenious scheme, due to Purcell and Koomen,[25] makes use of an occulting disk with sharp teeth which extend beyond its normal diameter. Although their explanation of the operation of such a disk—that the teeth diffract perpendicularly to their straight surfaces and thus do not scatter light into the objective aperture—does not emphasize the physics of the diffraction process, their requirement that the teeth have extremely sharp bottoms is seen to be a natural one from the mathematical development. A second form of the apodized occulting disk is one attached to a radially symmetric filter whose transmission changes from nearly zero at the edge of the completely opaque disk to unity at a larger radius. The obvious disadvantage of such a scheme—that irregularities in the

filter medium diffract light into the objective aperture—would seem to prevent its use in a practical device. A third apodizing scheme makes use of a second occulting disk behind the first partially to obscure the objective lens as seen by the Fresnel zones immediately above the first occulting disk. Since the second occulting disk is illuminated by weak radiation diffracted by the first, it may in turn diffract radiation into the objective aperture. Thus, to make the obscuration factor a_j sufficiently small, we may wish to add a third occulting disk behind the second. Since the toothed wheel as an external occulting disk has been thoroughly discussed by Purcell and Koomen,[25] we shall proceed immediately to the detailed description of the multiple disk.

As can be seen in Fig. 8, both the toothed wheel and the multiple occulting disk eliminate the bright diffraction spot in the center of the shadow. To make a quantitative comparison of these various occulting schemes we used a ribbon filament lamp as a synthetic sun and measured the light diffracted into a small aperture in the center of the shadow. The efficacy of the second occulting disk is immediately apparent in Fig. 9, which shows the reduction in the flux into the objective aperture as a function of the position of the second occulting disk. The maximum reduction occurs just when the second and smaller disk completely obscures the objective lens from the edge of the first disk. The addition of a third occulting disk produces a further reduction in the flux falling on the objective aperture. It is of interest to note that the use of only disks Nos. 1 and 3 of the three-disk configuration produces a somewhat poorer flux reduction than that accomplished by all three disks. The performance of these various occulting schemes is summarized in Table II. The logical extension of the three-disk occulter, an occulting disk with many components spaced between the positions of disks Nos. 1 and 3, performs somewhat less well than does the three-disk system. While the system with 170 disks should behave as well or better than the three-disk system, the inevitable irregularities in the disks undoubtedly throw spurious radiation into the objective aperture. Thus, by the use of a multiple occulting disk of appropriate design, we can bring about a reduction in the flux into the objective aperture of the

Table II. Comparison of Occulting Disks Illuminated by an Extended Source of 32 Min of Arc Diameter

Type of disk	d-$d_\odot$ (min of arc)	$F/F_\odot$
Single	10.6	3.5×10^{-3}
Double	12.0	8.0×10^{-4}
Double (disks #1 and #3 of triple disk)	14.0	3.8×10^{-4}
Triple	14.0	2.6×10^{-4}
170 disk cone	14.0	3.4×10^{-4}

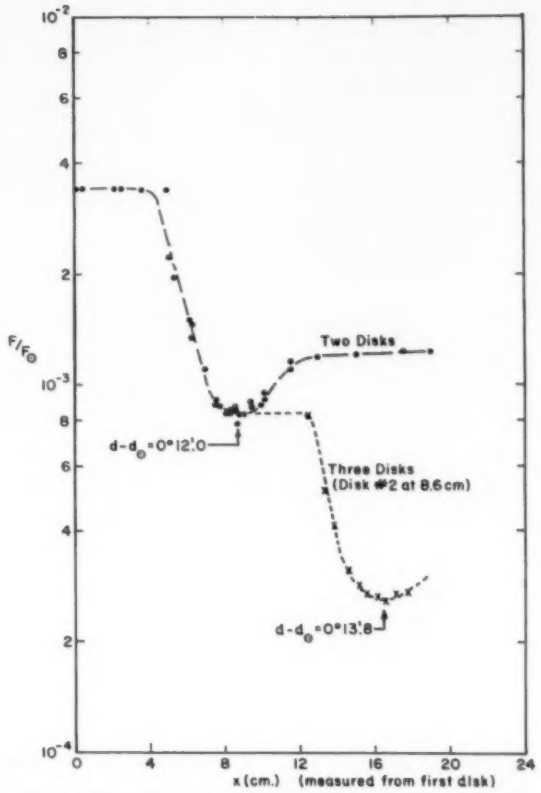


Fig. 9. Reduction of flux into an objective aperture by two- and three-disk occulting systems plotted as a function of the spacing between the disks. The experimental arrangement was the same as was used in the measurements shown in Fig. 6 with the first disk placed 76 cm from the objective aperture and the other disks placed x cm toward the aperture.

coronagraph and thus a reduction in the stray light in the coronagraph of approximately 2.6×10^{-4}. This represents an improvement of approximately a factor of 13 above the performance of the simple externally occulted disk coronagraph. *Since this implies that the stray light in the complete coronagraph would be approximately 8×10^{-10} of the mean solar disk, such a design appears useful for a wide variety of both satellite and balloon-borne experiments.*

We might say a word concerning the comparative advantages and disadvantages of the two occulting schemes—the multiple occulting disk and the toothed wheel. Purcell and Koomen have obtained a reduction in the shadow of a toothed-wheel occulter illuminated by a point source of approximately a factor of nine over the simple disk. This reduction compares favorably with that produced by the multiple disk. Our tests of a toothed wheel with an extended source subtending 32 min of arc produced an improvement of only a factor of two over the simple disk; however, we attribute the poor performance of our toothed wheel to irregularities

Table III. Comparison of Balloon-Borne and Satellite Coronagraphs

Item	Balloon	Satellite
Lifetime to meteoric exposure		10^6 to 10^7 sec in normal exposure 10^4 sec during meteor shower[28]
Lifetime to x-ray and ultraviolet aging		Greater than 10^6 sec
Estimated observing period	8 hr (2.9×10^4 sec)	30 days (2.6×10^6 sec)
Data recording	Photographic, recovered	Telemetry of scanned image
Information content per image	50 intensity grades over 2.8×10^4 locations (1.7×10^6 bits per photograph)	(Same)
Information rate	2.8×10^3 bits per sec assuming a 1-min exposure	20 bits per sec (*total* rate of information processing of OSO-1)
Information content per flight	8.2×10^7 bits	2.6×10^7 bits
Number of images per flight	4.8×10^2	1.5×10^2
Time required to produce one image	60 sec	8.5×10^3 sec (2.4 hr)

in the structure of the teeth. This difference immediately points to a disadvantage of the toothed occulting disk—the difficulty in making a toothed wheel accurately enough to realize the full capabilities of the apodized occulting disk. The relative ease of fabricating accurately machined disks of controlled diameter for a multiple occulting disk is, however, compensated by a disadvantage of the multiple occulting scheme—the series of disks must all be accurately aligned on the optic axis of the system.

Comparison of Externally Occulted Coronagraphs Carried in Balloons or Satellites

Since it is possible to construct a coronagraph having an instrumental background only slightly different from that encountered during total solar eclipse, it is wise to compare the advantages and disadvantages of such an instrument when carried either on a satellite or on a balloon (Table III). Since both devices would be limited by the level of internally scattered light, both can be expected to detect the corona out to approximately six solar radii.

Perhaps the most remarkable difference between the two systems is the length of the observing periods. Another important difference exists in the rate at which they gather images of the corona. Assuming that both coronagraphs have an angular resolution of one minute of arc, we find that approximately 2×10^4 image points exist in the field. If we are to distinguish 50 intensity grades at each one of these locations, six bits per location—1.7×10^5 bits per complete image of the corona—are required. Although the present satellites suffer from their low data handling capacity (20 bits per second for OSO-1), both systems gather approximately the same number of images per flight. Clearly, the second generation satellites, with their vastly improved telemetry systems, will be able to carry a coronagraph which can produce images of the corona at the same rate as the balloon-borne version. At the present time, however, the two coronagraphs can perform two complimentary and important functions The balloon-borne instrument, being capable of producing fairly rapid photographs for a relatively short period, can give information on the transient phenomena; the satellite-borne instrument, on secular changes. Without both types of information our knowledge of the solar corona will be severely limited.

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Auxiliary Optical Systems for the Kitt Peak Telescopes

D. H. Schulte

Descriptions are given of some of the more unusual optical systems to be used in the testing and the research program implimentation of the large Kitt Peak instruments.

The Observatory and Its Facilities

For readers who are not yet familiar with Kitt Peak National Observatory a short description of its organizational structure and general physical layout may be in order. The Observatory is operated under contract with the National Science Foundation by the Association of Universities for Research in Astronomy (AURA), Inc., a group of nine universities with flourishing graduate astronomy programs and experienced in the operation of astronomical research facilities. It is the policy of the Observatory to make available observing time with its instruments to those qualified astronomers and graduate students having need of them for their research programs. The Observatory now consists of three scientific Divisions: (1) The Solar Division, for studies of the sun, (2) The Stellar Division, for studies of astronomical objects other than the sun, and (3) The Space Division, whose long-range goals include observation of astronomical objects from above the earth's atmosphere.

The Observatory's main offices, laboratories, and shops are located in Tucson, Arizona. The observing station is located on Kitt Peak Mountain (elevation 2072 m) 53 km from Tucson. Telescopes now in operation include two 41-cm (16-in.) $f/13$ Cassegrains and a 91-cm (36-in.) $f/13$ Cassegrain (soon to be made convertible to an $f/7.5$ Ritchey-Chrétien). Two larger instruments scheduled for completion in 1963 are the 213-cm (84-in.) $f/7.5$ Ritchey-Chrétien stellar telescope and the 152-cm (60-in.) $f/60$ solar telescope, by far the world's largest. All of these instruments have been well described elsewhere in the literature,[1–4] and this article will be mostly concerned with the auxiliary optical systems which are needed in all cases except for direct photography to produce astronomical data from the photons gathered by the large "light-collectors."

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Optical Designing Equipment

The most common auxiliary instrument, with the probable exception of the photoelectric photometer, is the grating spectrograph. Bowen[5,6] has shown the relationships that exist between dispersion, plate resolution, and diameter of seeing disk on the one hand and spectrograph aperture and focal length on the other. For a given large telescope these relationships lead to a family of spectrographic cameras which for low-dispersion work can have very fast $f/$ratios.

Table I lists the family of Schmidt cameras which provides a suitable range of dispersion for the 213-cm telescope. It is in dealing with the design of the short $f/$ratio, flatfield types that the optical designer feels fortunate in having access to modern computing machinery. The Kitt Peak equipment used

Table I. Spectrograph Cameras for 84-in. (213-cm)Telescope

Focal length (cm)	F-ratio	Location	Dispersion with available gratings (Å/mm)	Corrector plate	Field flattener
7.6 (focusing in glass)	0.75	Cassegrain	78 –400	Yes	Yes
15.2	1.5	Cassegrain	39 –200	Yes	Yes
34.3	1.5	Coudé	24.3–48.6	Yes	Yes
61.7	2.7	Coudé	13.5–27.0	Yes	Yes
93.7	4.1	Coudé	8.9–17.8	Yes	No
134.9	5.9	Coudé	6.2–12.4	Yes	No
240.0	10.5	Coudé	3.5– 7.0	No	No
365.8	16.0	Coudé	2.2– 4.4	No	No

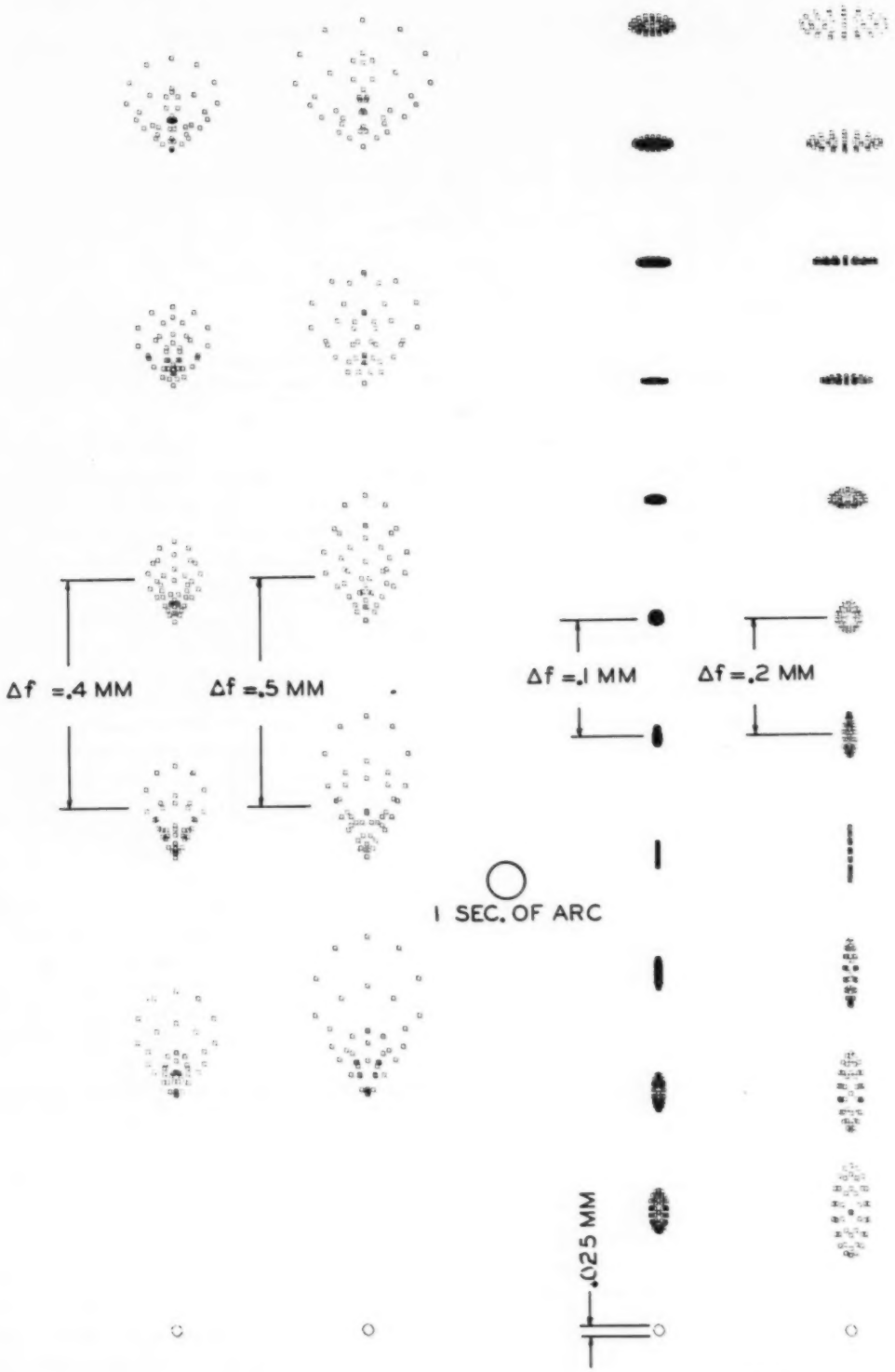

Fig. 1. (A) Spot diagrams near the best focus for 84-in. (213-cm) $f/2.62$-$f/7.5$ Cassegrain telescope at 10 and 15 min of arc off axis. (B) Same, for Ritchey-Chrétien configuration. All diagrams are to the same scale, as indicated by the plotter-drawn 25-μ-scale circles at the bottom. The focus increments are equal within each column but are made larger as indicated when larger aberrations are present.

for the designs in this paper were the Royal McGee LGP-30 and the Control Data CDC 160 computers. These are in the "small computer" category, making feasible operator intervention for parameter adjustment and progressively more stringent evaluation as the design progresses.

The most general type of optical surface which can at present be specified in the optical programs is of the form

$$X = \frac{cs^2}{1 + \sqrt{1 - c^2 s^2 (1 - e^2)}} + b's^2 + c's^4 + d's^6 + e's^8 + f's^{10};$$

where

c = curvature,
e = eccentricity,
s = semiaperture.

This family of surfaces includes spheres, ellipsoids, hyperboloids, and paraboloids (and even oblate spheroids if e^2 is negative), each with or without the deformation terms $b's^2, \ldots$ etc. For the special case of spherical surfaces the well-known skew ray-tracing expressions are used, while for all other types of surfaces the iterative ray-tracing scheme outlined by Feder[7] is used. For calculation of the surface contributions to the third order aberrations, paraxial ray traces are carried through for two fictitious paraxial rays—one from the on-axis object point to the edge of the entrance pupil, and one from the extreme off-axis object point to the center of the entrance pupil. It is planned to add fifth order calculations to the programs for the new 160-A computer. For the final evaluation of a system, the CDC-Calcomp on-line plotter is used to produce spot diagrams. Examples of this technique are shown later. Equally spaced rays are traced from the entrance pupil (circular in shape in the cases discussed here) through the system, and the parameters defining the emergent rays are punched on tape. This tape may be entered into storage under control of a program which then plots the ray intersections with an arbitrary image plane. After one set of intersections is plotted, the position of the image plane is incremented to simulate a focusing adjustment, and the procedure is repeated until the best focus has been passed. Spot diagrams for different wavelengths may be plotted side by side, or superimposed to show the effect of lateral color or chromatic variation of aberrations in integrated light. At present the distribution in the entrance pupil of the rays ultimately plotted is as follows: Eighteen through the edge zone, fourteen through the 0.8 zone, ten through the 0.5 zone, and the chief ray. (Only one ray of each symmetrical pair is actually traced, of course.)

The 213-cm (84-in.) Telescope

Before we proceed to the spectrograph camera designs, a discussion of the 213-cm system and testing procedures used for it may be of interest. The Ritchey-Chrétien design, as is well known, employs a near-hyperboloidal primary and secondary, both departing farther from the base sphere than either of their counterparts in the Cassegrain. The resultant improvement in the images due to the removal of the coma term is shown in Fig. 1. (Cf. Ritchey's[8] account of laboratory tests made at Paris.) For aplanatic telescopes of this type the angular diameter D of the astigmatic circle at a field angle θ may be determined from the relationship (cf. Danjon and Couder,[9] pp. 163, 195)

$$D = \frac{(2 - t_1)\theta^2}{4 t_2 F};$$

F is the final f-ratio, t_1 is the spacing of the two mirrors, and t_2 the back focus, measured from the secondary. The unit of length is the equivalent focal length of the system. Since t_2 and F tend to be inversely proportional for a given primary f-ratio and since the quantity $(2-t_1)$ changes only slowly, the result is that the performance of a Ritchey-Chrétien system depends more upon the choice of primary f-ratio than upon the amplification, i.e., *final* f-ratio. Figure 2 summarizes the results of calculations of a number of typical systems; the agreement is good between exact calculations and the above third order equation. The curves for the three primary f-ratios are quite narrow for final f-ratios of 7.5 and longer. As $f/5.0$ (final) is approached, each curve rises slightly, amounting to about $^1/_2$ sec at the 35 min abscissa (Table II).

At the adopted primary f/ratio of $f/2.62$, the maximum departure of that surface from the nearest sphere is 125 fringes. The procedure in the optical shop was

Table II. 84-in. (213-cm) Ritchey-Chrétien Telescope e.f.l. = 1620.1 cm

Surface no. (n)	Type of surface	Vertex radius (cm)	Distance to surface $n+1$ (cm)	Glass type to surface n and $n+1$	Remarks
1	Aspheric (see remarks)	−1116.8	−388.5	Reflection in air	X(cm) = $-4.4769 \times 10^{-4} s^2$ $+9.562 \times 10^{-12} s^4$
2	Aspheric (see remarks)	−518.6	+493.0	Reflection in air	Hyperboloid w/eccentricity = 2.336
Focus	—				

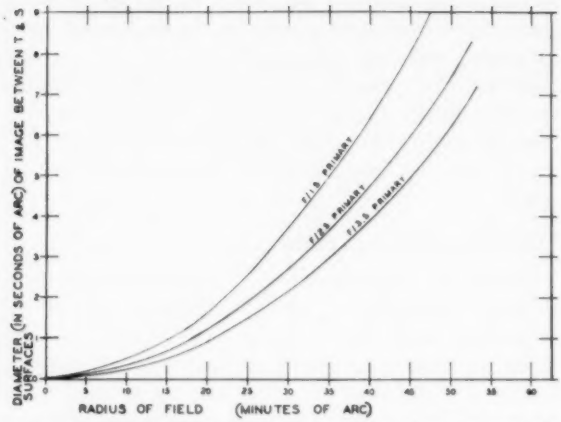
DIAMETER (IN SECONDS OF ARC) OF IMAGE BETWEEN T & S SURFACES
RADIUS OF FIELD (MINUTES OF ARC)
f/5 PRIMARY
f/3.5 PRIMARY
f/3.0 PRIMARY

Fig. 2. Relationship between blur circle diameter and distance off axis for Ritchey-Chrétien telescopes having primaries of differing f-ratios. The curves remain nearly unchanged for differing final f-ratios, as long as primary and secondary are rematched in each case to yield a coma-free system.

to figure the primary to the nearest sphere to insure absence of astigmatism introduced in the grinding, and then to figure the surface to the approximate Ritchey-Chrétien curve by zonal knife-edge testing. Smoothness of the figure was by then impossible to judge, and the null lens shown in Fig. 3 was introduced. The large lens forms an aberrated image of the pinhole near the position of the small lens. The range of axial intersection of the rays in an $f/5.3$ cone is made equal to the total variation in radius of the primary. The small lens, without appreciably changing this longitudinal aberration, slightly redirects the rays to strike the primary mirror surface perpendicularly in all zones. This can be done with sufficient accuracy to permit reimaging of the pinhole within a circle 8 μ in diameter or about $^1/_4$ sec of arc (λ 5461 Å) at the effective focal length of the system (Table III). This type of null tester was suggested by A. Offner of the

Fig. 3. Optical layout of radius null-tester for the 84-in. (213-cm) primary.

Perkin-Elmer Corporation (private communication) who used a similar lens to test the 91-cm (36-in.) $f/4.0$ Stratoscope II paraboloid (see Offner, this issue). Figure 4 is a set of four reproductions of knife-edge photographs through the null tester, showing the progressive improvement of the figure on the indicated dates. For scale reference the measured amplitude of the small ripples near the edge, as they appear on the second photograph, was not more than $^1/_8$ wave. For these tests it was necessary, owing to space limitations in the optical shop, to fold the optical path with two small flats, which, since one was hung inverted, introduced some uncertainty into the test results. Further testing was thus stopped and at this writing the primary is being placed in its permanent mounting. It will be tested by standard Hartmann procedures at the prime focus, the over-corrected spherical aberration of the Ritchey-Chrétien curve being allowed for in the reductions. The circle of confusion is over 10 sec of arc in diameter, and therefore knife-edge testing for smoothness and rotational symmetry would again be insensitive. However, the spherical aberration is nearly pure third order, and a 10-cm diam achromatic doublet (Table IV) with slight positive net power reduces the image size to less than $^1/_4$ sec of arc over a 1000 Å range, making knife-edge photographs of star images feasible.

Table III. Null Tester for 84-in. (213-cm) Primary (Center of Curvature)

Surface no. (n)	Type of surface	Vertex radius (cm)	Distance to surface $n+1$ (cm)	Glass type between n and $n+1$	Remarks
1	Spherical	∞	+1.60	$n_e = +1.51899$	
2	Spherical	−17.37	+54.03	Air	
3	Spherical	∞	+0.76	$n_e = +1.51899$	
4	Spherical	−53.18	+1118.4	Air	
5	Aspherical (see remarks)	−1116.8	−1118.4	Reflection in air	(Primary mirror) X(cm) = $-4.4769 \times 10^{-4}s^2$ $+9.562 \times 10^{-12}s^4$
6	Spherical	−53.18	−0.76	$n_e = -1.51899$	
7	Spherical	∞	−54.03	Air	
8	Spherical	−17.37	−1.60	$n_e = -1.51899$	
9	Spherical	∞	−81.90	Air	
10	Focus (front and back)	—	—	—	

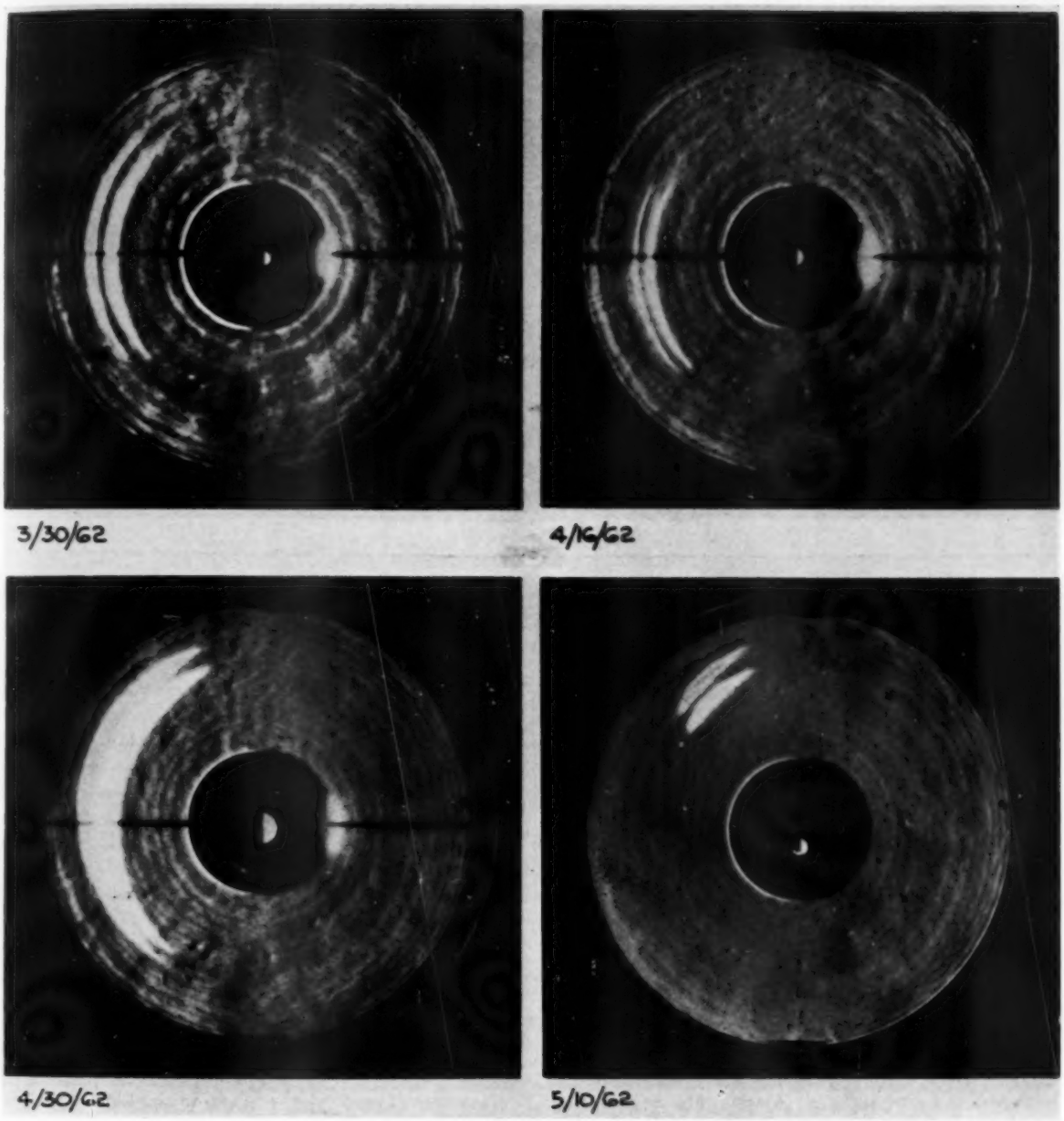

Fig. 4. Knife-edge photographs of the 3.1-m primary through the radius null-tester. The very light sections between "7 and 11 o'clock" are internal reflections in the null lens.

The Ritchey-Chrétien secondary, being sufficiently well approximated by an hyperboloid with foci shifted relative to an equivalent Cassegrain secondary, is being null-tested independently. From a pinhole placed at the front focus of the secondary the spherical wave front remains spherical after reflection, permitting reimaging of the pinhole by a 127-cm diam spherical test mirror.

Spectrograph Cameras

It will be noted that the coudé spectrograph cameras listed in Table I are of three general types: simple spherical mirrors with center of curvature at the grating, classical Schmidt cameras, and flat-field Schmidt cameras. The first two types need no further discussion. The $f/2.8$ and $f/1.5$ are representatives

Table IV. Null Tester for 84-in. (213-cm) Primary (Prime Focus)

Surface no. (n)	Type of surface	Vertex radius (cm)	Distance to surface $n+1$ (cm)	Glass type between n and $n+1$	Remarks
1	Aspherical (see remarks)	−1116.8	−533.0	Reflection in air	(Primary mirror) $X(\text{cm}) = -4.4769 \times 10^{-4}s^2 + 9.562 \times 10^{-12}s^4$
2	Spherical	−33.09	−0.97	B & L BSC-2	
3	Spherical	+42.80	−0.64	B & L DF-2	
4	Spherical	−297.1	−18.60	Air	
5	Focus	—	—	—	

Table V. f/1.3 Flat-Field Schmidt e.f.l. = 9.70 cm

Surface no. (n)	Type of surface	Vertex radius (cm)	Distance to surface $n+1$ (cm)	Glass type between n and $n+1$	Remarks
1	Aspherical (see remarks)	+376.	+0.63	Fused quartz	$X(\text{cm}) = +1.33 \times 10^{-3}s^2 - 6.10 \times 10^{-5}s^4 - 2.13 \times 10^{-7}s^6$
2	Spherical	∞	+16.64	Air	
3	Spherical	−20.32	−9.62	Reflection in air	
4	Spherical	−3.28	−0.23	Fused quartz	
5	Spherical		−0.23	Air	
6	Focus	—	—	—	

of the Meinel type of flat-field Schmidt.[10,11] This family of cameras is the subject of an investigation now in preparation. The final designs for the $f/2.8$ and $f/1.5$ are awaiting the completion of this investigation, which will permit the choice of optimum designs from members of this family, given specifications of desired performance. Therefore, in the interest of confining this discussion to completed optical systems, or those nearly so, the $f/1.3$ camera for the 91-cm spectrograph has been chosen as typifying the Meinel flat-field Schmidt (see Table V).

The present spectrograph for the 91-cm $f/13.0$ Cassegrain uses in its normal configuration an off-axis paraboloid for collimator, a 400 lines/mm reflection grating, and the $f/1.3$ camera. This combination yields 125 Å/mm dispersion in the second order and is ideal for spectral and luminosity classification of stellar sources. Figure 5 is the optical layout of the camera and shows the characteristics of the Meine system; the field flattener is located at a position relative to the focal plane intended to minimize its spherical aberration contribution. The coma also introduced is removed by placement of the corrector plate shortward of the center of curvature. The result is an improvement on the well-known design in which a plano-convex field flattener is used close to the focal plane (see Linfoot and Wayman[12]). The transmission optics are of fused quartz. The camera was designed in 1959 by Meinel before computing facilities were available at Kitt Peak Observatory. His previous experiences in building cameras of this type yielded, however, a design which has proved to be close to optimum. Figure 6 reproduces some typical spectra taken for spectral classification purposes. The spectrograph has been used for the preparation of an atlas of stellar spectra, now nearing completion. Due to its high resolution it has also been found useful for certain radial velocity programs. The probable error in radial velocity as determined from one plate has been estimated as ±4.5 km/sec. This is equivalent to a line-measuring precision of $\pm 1/2$ μ. Figure 7 shows the theoretical spot diagrams for the range 3500–5000 Å.

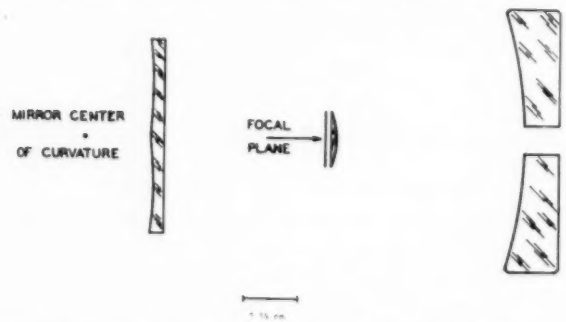

Fig. 5. Optical layout of the flat-field $f/1.3$ Schmidt camera.

To fill the need for lower-dispersion equipment on the 91-cm telescope (e.g., for spectral classification of galaxies), a design was made of a modified Hendrix thick-mirror Schmidt camera to be interchangeable with the $f/1.3$. This camera is effectively $f/0.6$, giving a dispersion of 275 Å/mm with the 400-line grating,

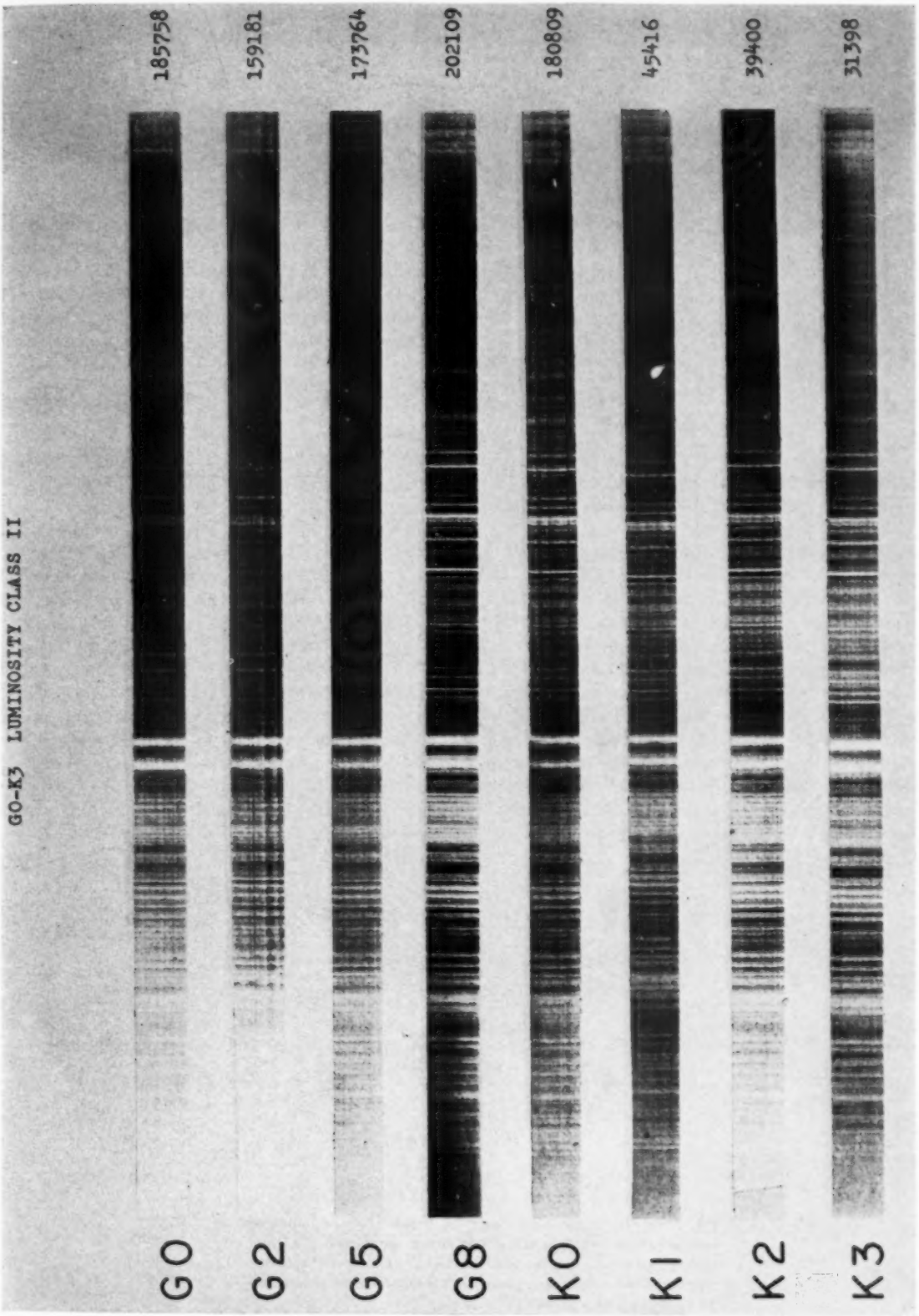

Fig. 6. Series of stellar spectra taken with the f/1.3 spectrograph camera at 125 Å/mm.

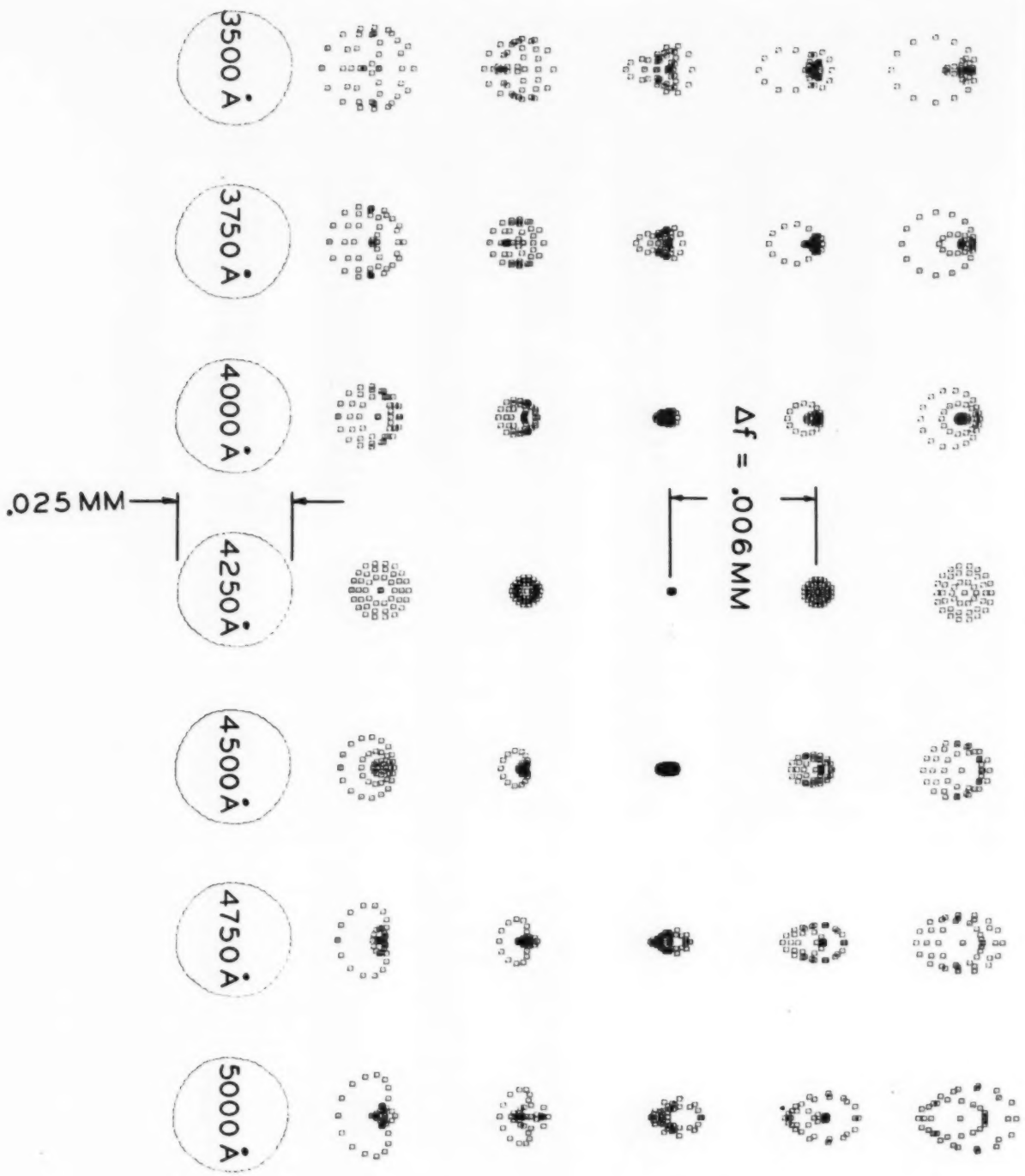

Fig. 7. Spot diagrams for the $f/1.3$ Schmidt at the indicated wavelengths and corresponding field angles assuming a 400 l/mm grating in second order, centered at 4250 Å. Each horizontal row represents the images on a plane tilted 8 min from perpendicularity to the optical axis.

and the improvement to include a flat field is achieved by an "air lens" field flattener. The thick mirror (see Fig. 8) and the plano-concave lens are of essentially the same crown glass, with the concave surface concentric with the mirror surface. The plano-convex lens is of flint, to minimize the curvature, and the focal plane is coincident with the slightly tilted flat surface of this lens. The corrector plate is again shifted inward from the apparent center of curvature of the reflecting surface, as seen by the latter through the thick mirror. Optical and mechanical parts of this camera are still under construction, and the difficulties with the tight tolerances involved have not been experienced as yet, but the theoretical optical performance illustrated in Fig. 9 indicates that good results are possible (see Table VI).

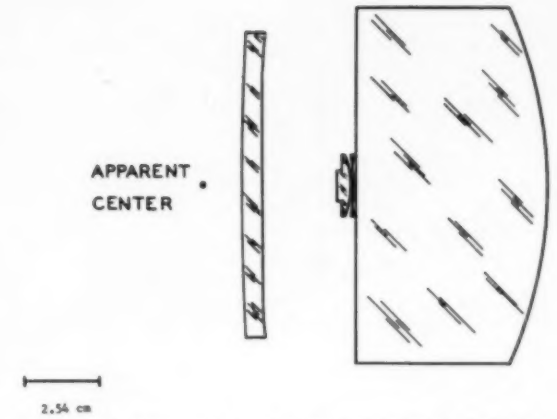

Fig. 8. Optical layout of the $f/0.6$ thick-mirror flat-field Schmidt camera.

Future Optical Work

Design and construction of Observatory instrumentation has proceeded at a high rate since 1960 and the next one or two years will see the completion of the first phase of this activity, when the 213-cm and solar telescopes are placed in operation. Optical and mechanical design work remaining to be done on the 213-cm instrumentation include the Cassegrain spectrograph and its cameras. A decision has not been made at present, for example, on the form which the short focus camera will take. Consideration will be given to the semisolid Schmidt with air and with sapphire field-flattener, and to the Bowen[5,6] aplanatic sphere version. If, as is hoped, the Observatory moves into its "second generation" phase which will involve large aperture space telescopes and very large-aperture earth-based telescopes, many more optical design projects will need to be undertaken. One, for example, is in the study phase now: an exploration of possible designs for prime-focus field correctors, both Ross-type and those using aspheric elements. It is probable that any larger-aperture telescopes will be relatively short ($f/3.0$ or less) to make most efficient use of future image tubes, and the design of field correctors for such $f/$ ratios is naturally complex. It will probably be necessary to evaluate many proposed designs, using, if possible, automatic optimization techniques developed by Feder,[12] Wynne (private communication), and others. The results of these studies may indeed influence the decisions concerning the design of the basic telescope. Finally, it is to be expected that the development of the space telescopes will create the need for design and testing techniques adapted to such large, diffraction-limited systems, and to their associated ultraviolet-sensitive auxiliary instruments.

Table VI. f/0.6 Thick-Mirror Flat-Field Schmidt e.f.l. = 4.55 cm

Surface no. (n)	Type of surface	Vertex radius (cm)	Distance to surface $n+1$ (cm)	Glass type between n and $n+1$	Remarks
1	Spherical	+100.0	+0.627	Schott BK-7	
2	Aspherical (see remarks)	−1767.	+3.150	Air	$X(\text{cm}) = -2.83 \times 10^{-4}s^2 + 2.42 \times 10^{-4}s^4 + 1.51 \times 10^{-6}s^6 + 7.88 \times 10^{-9}s^8 + 5.84 \times 10^{-10}s^{10}$
3	Spherical	∞	+6.335	Schott BK-7	
4	Spherical	−14.25	−6.335	Reflection in BK-7	
5	Spherical	∞	−0.152	B & L BSC-2	
6	Spherical	−7.766	−0.018	Air	
7	Spherical	−2.945	−0.437	B & L DF-2	
8	Focus	—	—	—	

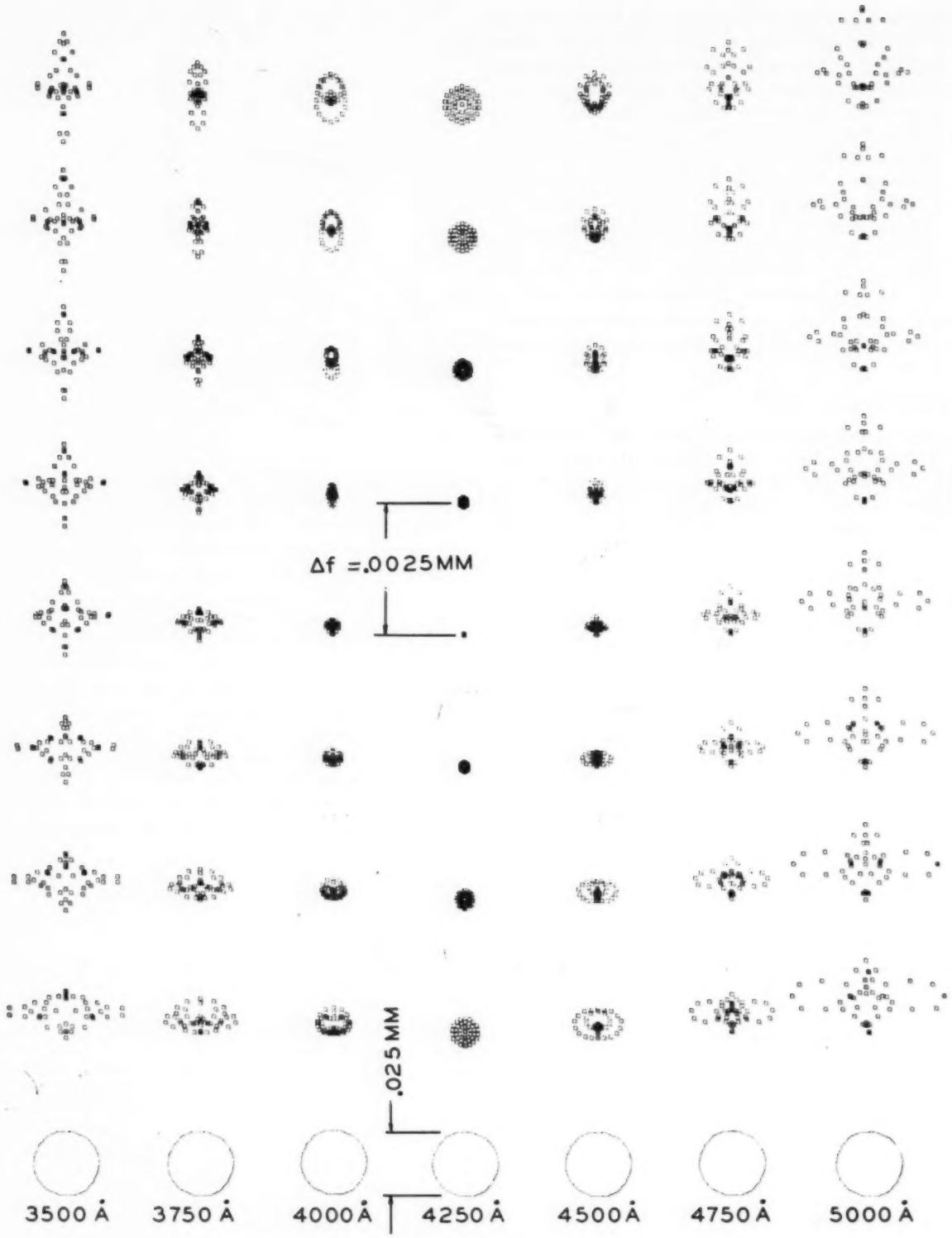

Fig. 9. Spot diagrams for the $f/0.6$ Schmidt, under the same conditions as Fig. 7, except that the plate tilt here is 40 min.

In reporting work such as this involving optical and mechanical design and optical and mechanical fabrication, it is difficult to single out a few people for special mention. Rather than attempt to do this, we shall reduce the space by listing only the last names of the persons involved:

At the Observatory: Drs. Mayall and Pierce, Mrs. Cardemil, and Messrs. Aurand, Cole, Harrison, Kirk, Loomis, Mackrill, Richardson, and Wilson. University of Arizona: Dr. Meinel. Perkin-Elmer Corporation: Messrs. Dodgen and Offner. Control Data Corporation: Messrs. Becker and Urbain. Imperial College, London: Dr. Wynne. In the preparation of this article, the writer was assisted by Mrs. Ingle, Miss Calhoon, Mr. Clark, and Mr. Slaughter.

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Applied Optics — Letters to the Editor

Letters to the Editor should be addressed to the Editor, APPLIED OPTICS, 1155 16th St., N.W., Washington 6, D.C.

Correlation of Output Spikes from Different Portions of a Ruby Laser

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Many basic questions relating to laser properties are still unanswered. The output of a ruby laser occurs as microsecond duration spikes termed relaxation oscillations.[1] The emission does not occur uniformly over the end of the rod but arises from small emitting areas.[2] These facts indicate that the processes occurring in a laser are complicated. The relationship of these spatial and temporal variations should shed light on the basic laser processes. This note describes an experiment in which the oscillatory outputs from different sections of a ruby laser rod are correlated.

Ruby rods with partially transmitting aluminized coatings on the flat ends were used in a helical configuration in which the ruby was cooled by flowing gas. On each end of the ruby an aluminum plate with a small hole (approximately 100 μ) was mounted. The plates were held firmly in place with a mechanical clamping arrangement. A photomultiplier tube viewed each end of the ruby through a metal tube arranged so that only light passing through one of the small holes could reach the photomultiplier. Sufficient filters were used to keep the phototube outputs in the linear region. Plates with holes in different positions were used, and the plates could be rotated relative to the end of the ruby. In this way different portions of the ruby end could be examined. Taking the outputs from different sections of the two ends insured no interference between the two beams being extracted.

In these measurements, five ruby rods obtained from various sources at different times were used. The rods were cut from raw material that ranged from 57°-oriented carrot-shaped boules produced in 1960 to annealed disk boules produced in late 1961. The same type of result was obtained from all the rods.

Typical relaxation oscillation spikes were observed in the laser emission emerging through the small holes in the plates. The general areas contributing to the laser output could be roughly mapped out using different positions of the holes. A typical trace on a dual-beam oscilloscope of the two photomultiplier outputs is shown in Fig. 1(a). The emitting areas were in this case on diametrically opposite sides of the rod. The same relaxation spikes were observed from each of the two holes. This result was quite general; whenever the holes were both over areas contributing to the laser emission, the same spikes were observed in both outputs. Even near threshold for laser action the same spikes appeared, as seen in Fig. 1(b), where the entire laser output consists of a small number of spikes.

The effect is not caused merely by scattered light emerging from the holes. Figure 1(c) shows the emission when the two holes were over roughly the same area. For Fig. 1(d) the plate over one end was rotated slightly so that the hole was over a position about 200 μ distant from its former location. The emission disappeared in this position, indicating that the light being observed really is that emerging from the area directly under the hole. Rotating the plate back to its approximate original position would restore the light output.

To test whether irregularities in the end coatings were responsible for these results, a ruby with end coatings removed was used, and the same results were obtained.

An interesting feature of these results is the observation of portions of the ruby surface that do not contribute to the laser action, even at pumping levels relatively far above threshold. When a hole was positioned over an area that did not contribute to the laser action, as for the top trace in Fig. 1(d), increased pumping intensity up to 2.5 times threshold did not stimulate laser action.

The relative amplitudes of the spikes were generally but not always the same on both traces. In a number of pictures rela-

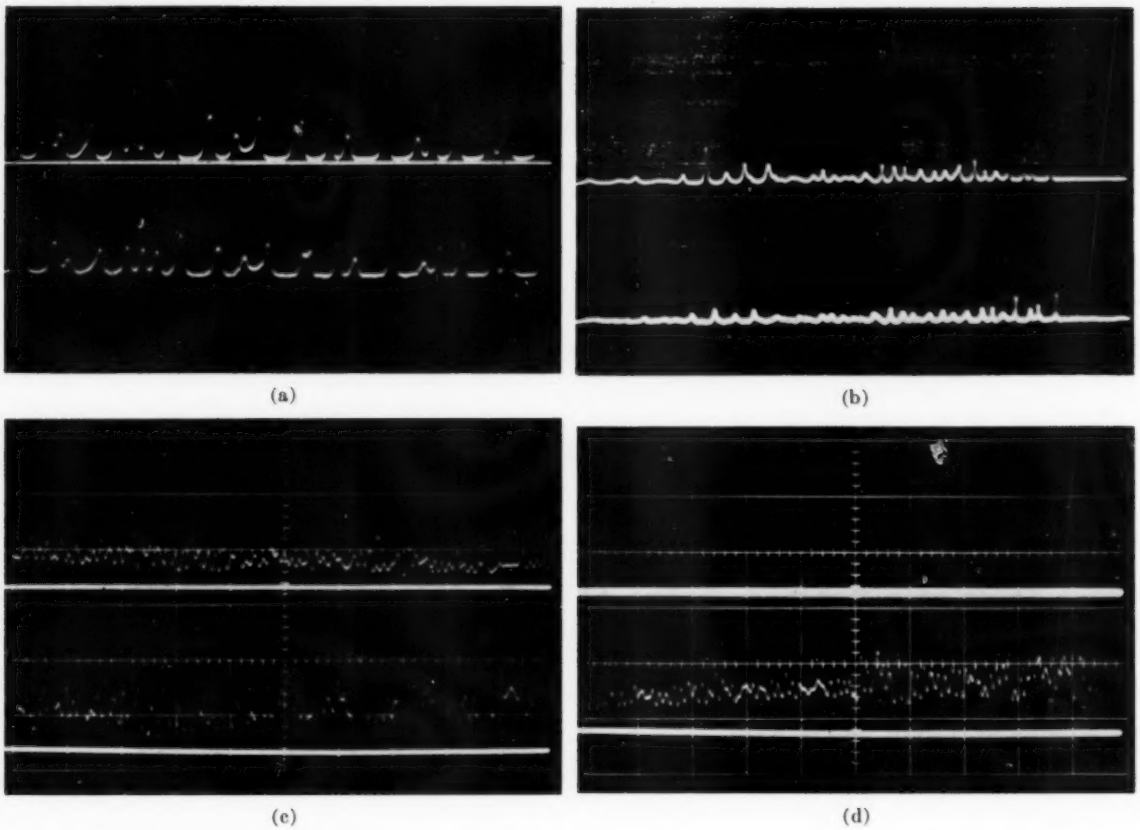

Fig. 1. Outputs of two S-1 photomultiplier tubes viewing the laser emission from two holes on opposite ends of a ruby laser rod. Time increases from right to left. The two traces are slightly displaced horizontally relative to each other by the triggering arrangement used. The upper frequency limit of the response of the photomultiplier circuit was 4 Mc. (a) Laser operated at 1.1 times threshold. The holes were on diametrically opposite sides of the rod. The time scale was 5 μsec per division. (b) Laser operated at 1.0 times threshold. The holes were on diametrically opposite sides of the rod. The time scale was 20 μsec per division. (c) Laser operated at 1.5 times threshold. The holes were over approximately the same area of the ruby rod. The time scale was 5 μsec per division. (d) Laser operated at 1.5 times threshold. The plate containing the hole giving rise to the top trace was rotated so as to move the hole to a position about 200 μ distant from its location in Fig. 1(c). The plate containing the hole giving rise to the bottom trace was in the same position as in Fig. 1(c). The time scale was 5 μsec per division.

tively large spikes appeared on one trace while the corresponding spikes on the other trace were relatively small.

Different areas also contributed at different relative levels of intensity as the input energy was changed. At low pumping levels it is possible that certain areas exhibit gain, but not gain sufficient to overcome losses, and are fed by light scattered from regions that provide self-sustaining oscillations. At higher pumping levels these regions may beome self-sustaining and provide larger outputs.

It is surmised that the coupling between the different volumes of the ruby undergoing stimulated emission is provided by scattered laser light.[3] The use of high-speed framing cameras[4,5] to photograph the output from the end of a laser can also demonstrate the spatial and temporal correlations in the laser output. However, since the minimum detectable signal for a photomultiplier tube differs from that of a photographic film, this method may provide a more sensitive probe of these correlations, although the gathering of data will be slower.

The assistance of D. L. Hardwick in this work is gratefully acknowledged.

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A Null Corrector for Paraboloidal Mirrors

Abe Offner

A simple optical system consisting of two small lenses can be designed to take the place of a large flat in testing paraboloidal mirrors. Other aspheric concave mirrors can also be tested in this manner. The procedure for computing such a null corrector and the accuracy required in its manufacture and use are discussed.

In making a large mirror, the limit of the accuracy which a good optician can achieve is set by the magnitude of the mirror errors which he can see or measure. When a large enough flat is available, it is customary to test paraboloidal mirrors during the progress of the work by the well-known Foucault knife-edge test. The light source and knife edge are placed at the focus of the mirror and the flat is used to reflect the collimated light coming from the mirror back to the mirror. This method is very sensitive and gives easily interpretable results if it is assumed that the errors of the flat are small compared to the maximum error allowable in the mirror.

In the project known as Stratoscope II, sponsored by ONR, NSF, and NASA, the Perkin-Elmer Corporation is building a 91-cm telescope system for Princeton University. The telescope is to be carried by an unmanned balloon to a height at which the effect of the earth's atmosphere on its performance is essentially removed. A tolerance analysis indicated that if the system were to achieve its desired performance, the root mean square departure of the primary mirror surface from a paraboloid had to be no more than one fiftieth of a wave. To measure this magnitude of mirror error we felt it desirable to have auxiliary optics which are more easily made and calibrated than a 91-cm flat.

A spherical mirror can be tested easily with no auxiliary optics by putting the light source and knife edge at the center of curvature. All rays from the center of curvature proceed along normals to the spherical surface and are reflected back along the same paths so that even cutoff indicates a perfect sphere. Our object was to obtain a similar setup for paraboloidal mirrors with the help of small auxiliary optical elements which are easily made and measured.

It has been suggested that the spherical aberration of a paraboloidal mirror used at unit magnification can be compensated by a convex lens placed between the paraboloidal mirror and its "center of curvature,"[1,2] or by a spherical mirror placed beyond the "center of curvature."[2] In such tests it is desirable to place the compensating mirror or lens near the "center of curvature" of the paraboloid in order to keep its size down. F. E. Ross[2] showed, however, that one can decrease the residual uncompensated aberration over the aperture by increasing the distance between the compensating mirror or lens and the "center of curvature." This comes about because the third order spherical aberration introduced by the paraboloidal mirror can be balanced only by a combination of third and higher order aberration if the balancing is done at any position other than at the paraboloid, where the corrector would have to be as large as the paraboloidal mirror itself.

To get around this difficulty it was decided to correct the paraboloid by a lens which was placed at the paraboloid optically but not physically. A system for doing this is shown in Fig. 1. Here the field lens forms an image of the imaging lens at the paraboloid. This results in exact compensation provided that the spherical aberration introduced by the imaging lens is pure third order and of the proper amount to balance the "spherical aberration" of the normals to the paraboloid.

In practice it is not necessary that the spherical aberration of the imaging lens be pure third order, a requirement which is not always easy or convenient to attain. What is required is that the spherical aberration of the correcting system match the "aberration" of the normals to the paraboloidal mirror.

Figure 2 shows the "aberration" of the normals to a paraboloid. C is the center of curvature of the oscu-

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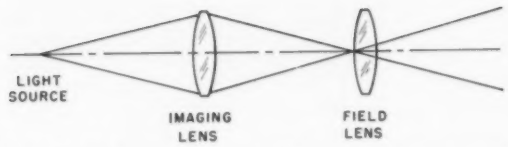


Fig. 1. Optical system for obtaining spherical aberration following a desired law.

lating sphere at P. The desired aberration of the null corrector is given by the relationship,

$$CD = (-R/2)\tan^2 U.$$

In the optical system of Fig. 1, the aberration will not be proportional to the square of the tangent of the slope angle, as desired, for any arbitrary shape of the imaging lens. If, now, the power of the field lens is changed, the third order spherical aberration of the system is unchanged but its "offense against the sine condition" is altered. This means that the relationship between the spherical aberration and $\tan U$ is changed. The power of the field lens can be varied until the spherical aberration of the system follows the desired law. The system can now be scaled to match the spherical aberration of the desired paraboloid.

The operation of this null corrector depends on the fact that a real image of the light source is formed at the center of curvature of the paraboloid. This affords a position for the field lens at an image plane at which spherical aberration is present. The shapes of the elements of the null corrector and the magnification at which it is used can be varied between wide limits.

The system actually used with the 91-cm $f/4$ paraboloidal primary mirror of Stratoscope II is shown in Fig. 3. The test system was designed to be used with mercury green light. Both elements are plano-convex. The larger one has a clear aperture of 45 mm.

It is interesting to compare the residual uncompensated aberrations of previous null correctors with those which can be achieved by the present arrangement. The H. E. Dall[1] corrector restricts the shape of the compensating lens to plano-convex. The resulting compensation is adequate only for relatively small aperture mirrors if a high degree of precision is required.

F. E. Ross[2] used the shape of the compensating lens as one of his parameters and was able to reduce the residual aberrations considerably. As a compensator for the 508-cm Mt. Palomar paraboloid, he used a lens of 25-cm aperture which, according to his computations, would have resulted in a paraboloid with a circle of confusion of 3.2 arc sec diameter. An aspheric corrector plate was added to this null corrector to make it adequate.

Scaling the null corrector of Fig. 3, to make it work with a 508-cm aperture paraboloid, results in a clear aperture of 25 cm for the larger lens, the same as the aperture of the null corrector lens used by F. E. Ross. The residual aberration of a paraboloid made with this null corrector would result in a geometrical circle of confusion of less than 0.01 arc sec diameter. Allowing a factor of 3 for the fact that the Mt. Palomar mirror is

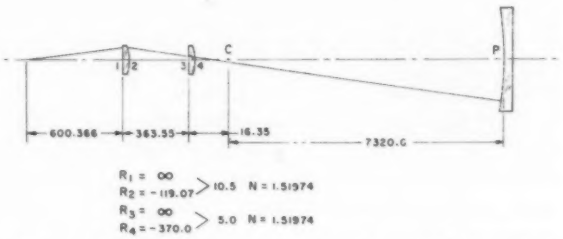


Fig. 3. Optical system used for null testing a 91-cm $f/4$ parabolic mirror at center of curvature.

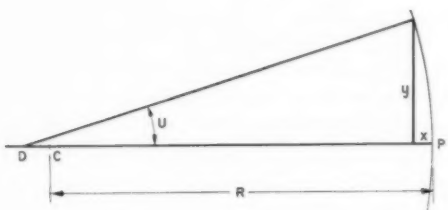
$f/3.33$ while the Stratoscope II mirror is $f/4$, one can see that the use of a field lens has resulted in a decrease of the uncompensated residual aberration by a factor of 100. If required, further improvement could be obtained by altering the shape of the imaging lens.

An investigation was made of the effects of small departures of the parameters of this system from nominal on the imagery obtained with a perfect paraboloid.

From its center of curvature, the paraboloid subtended an $f/8$ cone. The light source and knife edge were at an image plane which was magnified 1.57 times with respect to the center of curvature of the paraboloid so that the convergence at the knife edge was $f/12.6$. The radius of the first dark ring of the diffraction pattern in mercury e-light was therefore 8.4 μ.

A change of index of refraction of the elements of the corrector system of 0.0002 caused an enlargement of the geometric circle of confusion to 0.3 μ radius.

A change of radius of the large lens of 0.050 mm, which corresponds to a change of 1 μ in its saggita over its clear aperture, caused a geometric circle of confusion of 0.4 μ radius.



$$x = -\frac{y^2}{2R}$$

$$\text{TAN } U = -\frac{dx}{dy} = \frac{y}{R}$$

$$CD = x = -\frac{y^2}{2R} = -\frac{R}{2}\,\text{TAN}^2\,U$$

Fig. 2. "Aberration" of normals to a parabola.

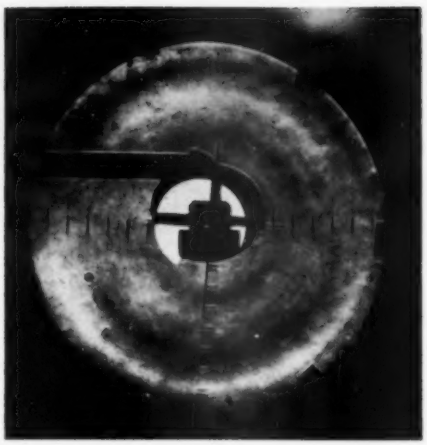


Fig. 4. Focogram of 91-cm mirror made by autocollimation off 100-cm flat.

Fig. 5. Focogram of 91-cm mirror made with null corrector shown in Fig. 3.

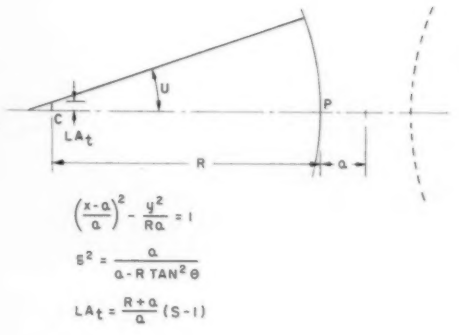


Fig. 6. "Aberration" of normals to a hyperbola.

A change in the separation of the two elements of 0.1 mm caused an increase of the geometrical circle of confusion of 0.6 μ radius.

Similar changes would be caused by changes in the thickness of either element by 0.15 mm.

An uncertainty in the location of the point C, the center of curvature of the osculating sphere to the paraboloid at its pole, would result in a parallel surface to a paraboloid in place of the paraboloid. A simple calculation showed that, for an error of 5 mm in the location of C, the resulting surface at perfect cutoff would depart from a paraboloid with the same radius of curvature at its pole by $^1/_{59}$ of a wave.

The null corrector can therefore be built to the required degree of accuracy without unusually tight tolerances. It must be made of highly homogeneous glass, and the figure of the large element must be better than that aimed for in the paraboloid. To meet the first of these requirements, the system was designed with Schott BK-7 glass which is obtainable with very good quality. Measurements with a Herriot type interferometer indicated a figure of better than $^1/_{20}$ of a wave in the elements as made.

Figures 4 and 5 show focograms of the primary mirror, one of which was made with the null corrector and the other of which was made by autocollimation with a 100-cm flat.

This method is of course not confined to the testing of paraboloidal mirrors. It is particularly useful in the manufacture and testing of hyperboloidal concave mirrors which are used as the primaries in Ritchey-Chrétien systems, since such mirrors cannot be tested by autocollimation with flats. One reason astronomers have avoided specifying these systems in the past in spite of their superior performance was the difficulty of manufacturing them. With the new null corrector, Ritchey-Chrétien primaries can be made and tested almost as easily as paraboloidal mirrors. Figure 6 shows the required spherical aberration of a system to be used for null testing a concave hyperboloidal mirror at its "center of curvature."

A null corrector was designed for the 102-cm primary of a Ritchey-Chrétien telescope being built for Mt. Stromlo Observatory in Australia by the Perkin-Elmer Corporation. The primary is an $f/3.5$ hyperboloid with an eccentricity of 1.1026. The larger lens of the null corrector system has a clear aperture of 52 mm.

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The Effect of Protective Coatings of MgF_2 and SiO on the Reflectance of Aluminized Mirrors

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Magnesium fluoride is commonly used as an antireflection coating for lenses. It is also occasionally used as a protective coating for aluminized mirrors and, in spite of convincing arguments to the contrary,[1] at least one optical firm recommends it rather than the more commonly used silicon monoxide. Very little data are available on the optical properties of MgF_2 coated mirrors. In addition, although the reflectance of aluminized mirrors coated with thick SiO films has been reported for the 0.25 to 35-μ wavelength region,[2-5] a direct determination of the reflectance decrease caused by the thinnest films used for protective coatings may be of interest. The coated aluminized mirrors measured in this laboratory were prepared commercially* and should be representative of mirrors coated with films of comparable thickness which are produced by any good optical shop.

In the measurements reported in this paper, the 38-mm diam optical flats used as substrates were all aluminized at the same time. One flat received no protective coat, the second a 752 Å SiO film, and the third a 1122 Å MgF_2 film. The reflectances of all the samples were measured using the reflectometer reported previously.[6] The thicknesses of the SiO and MgF_2 films were determined interferometrically[7] by measuring samples which were completely overcoated with opaque silver. Although the optical thicknesses were nearly the same, the physical thicknesses were considerably different because of the differences in the refractive indices of the two materials.

Figure 1 shows the difference between the reflectance of the aluminized sample and the aluminized samples coated with MgF_2 and SiO. As can be seen, neither film absorbs significantly in the region from 15 to 32 μ. In addition, neither film shows any particular optical advantage over the other in the entire wavelength range studied, although a slight decrease in the reflectance of the SiO coated sample caused by the well-known 9-μ absorption band can be observed. It thus appears that either SiO or MgF_2 may be used for protective coatings on aluminized mirrors without adversely affecting the infrared reflectance. However, mirrors for use in the visible and near ultraviolet should not receive a protective coating unless the increased abrasion resistance is really necessary and the luminosity of the optical system in which the mirrors are to be used is of secondary importance.

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* Prepared by Ferson Optical Co., Ocean Springs, Mississippi.

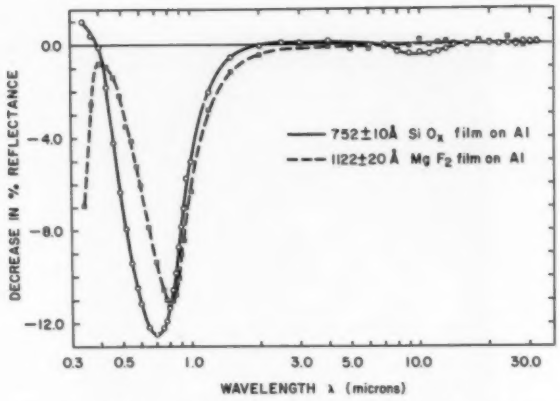

Fig. 1. Difference between the reflectances of coated and uncoated aluminized samples plotted as a function of wavelength.

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A Pre-Sputnik View of Astronomy

"I've learned one thing about the universe. There's no money in astronomy."

Drawing by Dedini © 1956 The New Yorker Magazine, Inc.

Image Orthicon Astronomy at the Dearborn Observatory

William T. Powers and Richard S. Aikens

For a given signal-to-noise ratio, the image orthicon can record stars to a theoretical magnitude limit set primarily by skylight. A "skylight suppression" technique under development appears capable of increasing available integration time and hence the limiting magnitude. Short exposure pictures of the moon under high magnification show about $^1/_2$-sec resolution with good seeing, and an 18.5-in. (47-cm) telescope; under certain conditions the image orthicon can be used to provide better resolution than possible with emulsions, owing to the shorter exposures which are feasible even with high-magnification projection optics. Among other electronic devices which have been used are the intensifier orthicon, the image isocon, and, most promising, the field mesh orthicon. Brief descriptions of these devices are given as a matter of general interest, although they are not in use at Dearborn Observatory. A list of some Dearborn Observatory projects in electronic astronomy is presented to suggest the wide range of application of this new technique.

Basic to research in modern observational astronomy are all methods of capturing, recording, and analyzing the often pitifully small radiation received on earth from stellar sources. The photographic process was the great breakthrough of the past century, and its continued improvement during this century has easily been the equivalent, in light-gathering power, of telescopes of impossibly large apertures. More recently the image orthicon tube has provided a new, powerful and flexible tool for the astronomer which, despite some limitations, again offers a significant improvement in the effective light-gathering power of existing telescopes. In this paper are discussed some aspects of orthicon astronomy which have been studied at the Dearborn Observatory.

Sensitivity of the Image Orthicon

Figure 1 presents a schematic drawing of an image orthicon tube showing two major sections, the image section and the scanning section. Let us consider the image section first.

Analysis of Image Noise

At the photocathode an image is presented, resulting in a flow of photoelectrons from photocathode to target. An axial magnetic field focuses the electrons (as they accelerate down a 600 V gradient) onto a target, a thin film of high resistance material (e.g., MgO or Al_2O_3). On reaching the target, each initial electron gives rise to five to seven secondaries, which are collected by the target mesh (through which the photoelectrons arrived). Thus a positive electrical image is formed, corresponding to the original optical image.

If we consider one small element of the photocathode, we may designate the photon flux received per unit exposure as N_p. If the quantum efficiency of the photocathode is e, then (eN_p) photoelectrons will strike the corresponding area of the target, leaving k positive charges per original photoelectron, for a total of (ekN_p) positive charges.

If we now invoke the necessary assumptions of linearity, and assume that photons, photoelectrons, and secondary electrons are all Poisson distributed and independent,* we can then compute the variance of the final electrical charge by use of the principle that Var $(ax) = a$ Var (x). This leads to the variance of the final target charge q_t being

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* It has been learned that Albert Arcese of RCA (Burlington, Massachusetts) has very recently developed an analytical proof that in processes of this type the second generation events are not Poisson distributed. This analysis has not yet been published and verified; the signal-to-noise ratio at the photo-cathode is given by Arcese as $[e/(e+1)^{1/2}]$ times the signal-to-noise ratio in the photon input. For many stages the expression rapidly becomes more complex. The results are presented with Mr. Arcese's kind permission. Under all conditions described in this paper image noise plays little if any part in limiting maximum performance, and is eliminated from Eq. (5) by a suitable approximation.

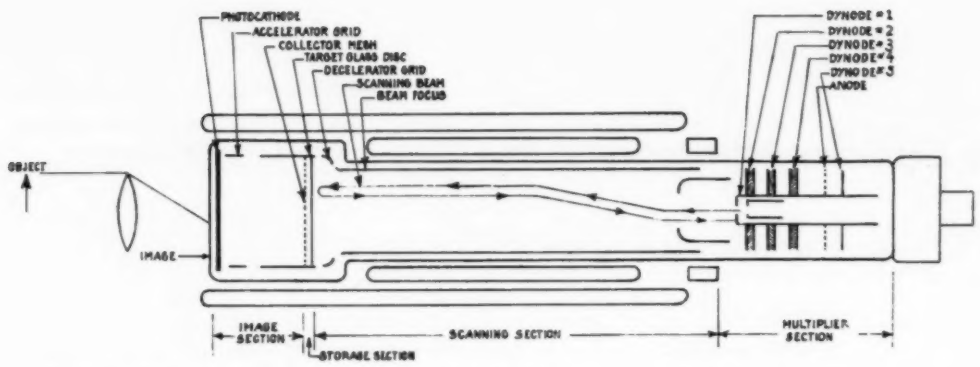


Fig. 1. Schematic of image orthicon showing deflection coils, focus coil, and internal structure of tube.

$$\begin{aligned}\mathrm{Var}(q_t) &= ek\ \mathrm{Var}(N_p) + k\ \mathrm{Var}(eN_p) + \mathrm{Var}(ekN_p)\\ &= 3ek\ \mathrm{Var}(N_p).\end{aligned} \tag{1}$$

With N_p having a Poisson distribution, the variance of N_p is just N_p, so the average rms noise in a stored image element is $(3ekN_p)^{1/2}$.

Signal-to-Noise Ratio

The readout process takes place at the end of an exposure, after an electrical image has been stored. An electron gun at the base of the tube generates an electron beam which is given an initial velocity and then travels against a potential gradient toward the target. Owing to the axial magnetic field these electrons fill an envelope of loops and nodes, coming to a focus at the target at one of the nodes. The focus spot consists of a small cloud of electrons which is magnetically scanned across the target, presenting each element of the target with some number of slow-moving electrons. A fraction p of the electrons leaves the cloud and discharges the element, and the remainder accelerates back down the gradient to be multiplied (by about 500) and collected. The factors governing the magnitude of p are not yet well known, but if we confine the argument to faint images we can assume a value of around 0.01. This value is an estimate based on the fact that under the operating conditions required for recording the faintest images, the current to the 3rd dynode (about 40 times the return current) is measured as 0.35 μA, implying a beam current of about 7.5×10^{-9} A. Signal-to-noise under these conditions, judged on oscilloscope traces, is about 2:1. With about 50,000 image elements being scanned in $^1/_{30}$ sec, the beam charge per element is about 3.4×10^4 electronic charges. The "noise charge" is thus 180 charges, and for 2:1 signal-to-noise ratio the effective charge due to an image is 360 charges. Dividing this figure by the beam charge per element gives about 1% modulation. It is immediately apparent that the electrons collected as a returning beam contribute a large amount of noise, far more than is present in the stored image.

We can describe the charge (q_b) presented by the scanning beam to an element of the target in terms of p and the charge (ekN_p) in the cell that is to be read:

$$q_b = \frac{ekN_p}{p}. \tag{2}$$

The variance of q_b may be taken as $q_b^{1/2}$, so that a complete expression for the signal (q_s) present as modulation of the beam becomes

$$q_s = ekN_p \pm (3ekN_p + ekN_p/p)^{1/2}. \tag{3}$$

To calculate the faintest one-element image detectable, an expression must be found for signal-to-noise ratio between two independent cells, one containing background photons alone and the other containing, in addition, photons from the source to be detected. This will cause beam noise to enter twice. Making appropriate substitutions into (3) and simplifying, we arrive at

$$S = \frac{ekN_{ps}}{\{ek\ [N_{ps}(3 + 2/p) + N_{pb}(6 + 2/p)]\}^{1/2}} \tag{4}$$

where

S = signal-to-noise ratio,
N_{ps} = no. photons due to signal,
N_{pb} = no. photons due to background.

Equation (4) becomes a limiting magnitude equation when rearranged and converted to a magnitude scale. The term "limiting" is given meaning by the number assigned to S, the least signal-to-noise ratio one can accept at the output of the orthicon (assuming dynode noise negligible) and still maintain the required probabilities of detection and false alarms per frame.

If sky brightness is defined in terms of equivalent solar magnitude per resolution element, one can then measure all pertinent factors at the output of the image orthicon; since these measurements have not been completed by Dearborn, we can give only estimated numbers to produce an approximate formula for limiting magnitude:

If the flux from a 13.0 mag star = 5.5 photons/sec cm², the receiving aperture = 18.5 in. (47 cm), 80% transmission, and $2/p \gg 6$ (allowing a simplifying approximation):

$$m_s = 2.5\left(5.2 - \log\left\{\frac{d}{7600}\,\frac{[1+(1+4QN_{pb})]^{1/2}}{2Qt}\right\}\right), \quad (5)$$

where

$Q = ekp/6S^2$,
d = no. resolution cells occupied by image of star as seen on final display,
t = exposure, sec.

And where N_{pb} is calculated from

$$N_{pb} = (7600)\,(2.512)^{(13.0-m_b)}$$

(m_b = sky effective magnitudes per element of final display). Note that the approximation used eliminates consideration of image noise, hence avoiding errors due to possible non-Poisson statistics mentioned previously.*

This equation yields the curves of Fig. 2, in which exposure time versus limiting magnitude is shown for $S = 1$, 2, and 4. When the output is presented on a P7 phosphor screen and photographed, one can distinguish stars from noise reliably at S equal to about 2. At $S = 4$, the background is dark, but faint stars are lost, while at $S = 1$, noise obscures faint stars. Thus while the data plotted on Fig. 2 do not constitute a test of the predictions, the parameter values which give a good fit are all reasonable. Note that "Q" above has an indirectly determined value: e and k are known to be about 10% and 6, respectively,† and by beam current measurements and oscilloscope measurements both p and S can be estimated (see discussion beginning this section).

Background Suppression

The foregoing analysis does not reveal a critical effect of sky background, namely, saturation of the target. An element of the target can accumulate charge only as long as its potential is less positive than that of the target mesh, because secondary electrons must be collected. If the target is "wiped clean" by several scans before an exposure, its potential is established several volts below that of the electron gun cathode, owing to the tail of the thermionic-electron distribution curve. If the target mesh were at the highest practical positive potential during this pre-exposure process, the target to target-mesh capacitance would be charged to its maximum value. When the skylight has essentially discharged this capacitance, not only does accumulation of information cease, but stored information is destroyed.

To avoid this effect, it is necessary somehow to deposit a negative charge periodically on the target during an exposure so as to cancel the general rise in potential due to background.[1] At Dearborn a method for doing this is being evolved.

The readiest source of negative charge is the scanning beam itself. Simply scanning with a low beam current will not accomplish the required objective, since image-points, being more positive than the general background, would attract more electrons and hence would be preferentially discharged. If, however, the target mesh potential is raised momentarily, the target proper will rise in potential, because of capacitive coupling, by about the same amount, with the result that, if a reduced scanning beam is turned on for one full frame, the entire beam can be collected on the target. The scanning electrons will now have several volts of velocity when they reach the target, and at least in the vicinity of weak images will distribute themselves uniformly.

If the charge deposited is just equal to that due to skylight since the last "intermediate scan," the background potential of the target will remain within operating limits.

An alternative method—that used for obtaining the results of Fig. 3—is to let the positive charge due to skylight serve for collecting the beam. If the target

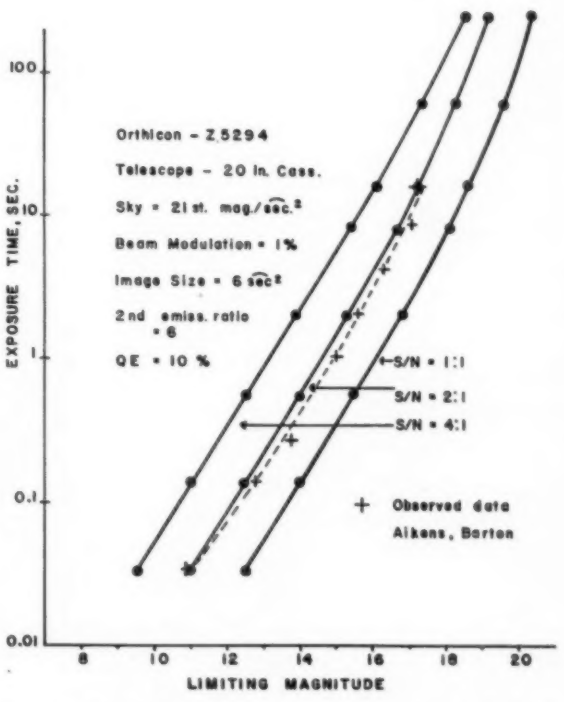
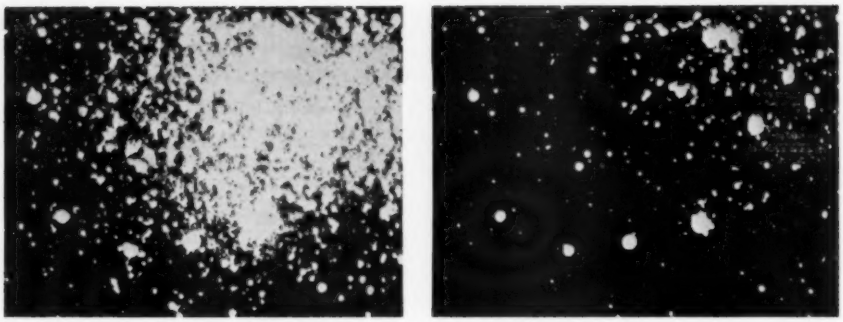


Fig. 2. Graph of exposure time vs limiting magnitude illustrating signal-to-noise ratios of 1, 2, and 4.

* See footnote on page 157.
† General Electric Co.; manufacturer's data.



SUPPRESSION OFF SUPPRESSION ON

Fig. 3. Corona Borealis taken with wide-angle lens ($f/2.8$, 135 mm f.1) showing effect of background suppression. 12-sec exposures: suppressing scans at 4 and 8 sec, right-hand picture only.

normally at +2 V is set to about 5 V, with all other electrodes at normal potentials, scanning with a much-reduced beam will not result in readout of an image if enough skylight charge has accumulated. This skylight charge can then be kept within the bounds necessary for avoiding saturation. This method has limits because of the delicacy of adjustment required in beam current; a two-level beam current switch with separate control of each level is essential. No complicated circuits are needed, however, as are required by the other method.

It has been found that the intermediate low-beam scans should be spaced as far apart as possible, both to provide sufficient positive charge on the target to collect most of the beam current and to render control of beam current less critical. The wide-angle picture of Fig. 3 was a 12-sec exposure with intermediate scans at 4 and 8 sec. Without suppression, 4 sec was the maximum usable exposure.

The intermediate scans will add noise to the picture—in fact, an amount equal to that which would have been contributed by uncanceled skylight—but at the same time the scanning current can be reduced by the amount that would have been needed to read the skylight.

To see the effect of sky suppression on signal-to-noise ratio, refer to Eq. (3):

$$q_s = ekN_p \pm \left(3ekN_p + \frac{ekN_p}{p}\right)^{1/2}. \tag{3}$$

When this equation is used to determine beam noise, the beam is assumed set to discharge an element containing image and background signals, so that beam noise contribution is given by (3a):

$$\text{Beam noise} = \frac{[2ek(N_{ps} + N_{pb})]^{1/2}}{p^{1/2}} \tag{3a}$$

(the factor of 2 appears because *two* independent cells are being considered).

If sky suppression is used, an amount of noise equal to that due to skylight, $(3ekN_{pb})^{1/2}$, is added by the intermediate scans, but the beam current necessary is reduced from $ek(N_{ps} + N_{pb})/p$ to ekN_{ps}/p. Thus a term $(2ekN_{pb}/p)$ disappears from the variance, and a term $6ekN_{pb}$ becomes $9ekN_{pb}$. The new expression for S is thus

$$S_{sup} = \frac{ekN_{ps}}{\{ek[N_{ps}(3 + 2/p) + N_{pb}(9)]\}^{1/2}}. \tag{4a}$$

The factor (9) replaces $[6 + (2/p)]$ in the original form; thus a moderate increase in signal-to-noise ratio can be expected when sky suppression is used, and p is less than 0.67.

It is important to note that Eq. (5) is a *relationship* between limiting magnitude and several parameters, including time. In principle there is no "limiting" magnitude because one can extend the value of M_s indefinitely just by extending the exposure time. The only limits are practical ones: that set by saturation of the sensor by background light, and the limits on maximum storage time. With cooled tubes, the latter limit may never be of practical importance; the limit set by saturation is what now determines the faintest objects attainable.

Thus when the performance of the system is not approaching the limit set by target saturation, operation in the sky-suppression mode makes no appreciable difference in principle, and in practice generates a slightly poorer performance owing to charge distribution *not* being perfectly uniform. When sky background is the limiting factor, however, considerable improvement is seen. Figure 3 demonstrates this effect. Because of vignetting and nonuniform illumination in the optical system (involving, for example, use of a handy 90-deg prism to avoid demounting the TV camera), the sky background is very nonuniform, so that around the periphery stars are lost, but in the center of the "whited-out" region, the saturated region is restored to a more normal-looking field of stars. In

the portion of the picture where sky suppression appears to be about correct, image diameters, an indicator of the amount of stored signal, do not appear to be significantly decreased. Toward the edges of the picture stars are lost because the suppression beam current was too high for the smaller amount of skylight collected there. Experimenters using properly mounted wide-angle optics will undoubtedly achieve better results than the first attempt shown here.

This technique is expected to be of value primarily when it can be used to extend exposure times beyond the limit normally set by skylight. When the $f/15$ Dearborn refractor is used, skylight is only important on hazy moonlit nights; tube cooling will be necessary before sky suppression can extend the light grasp much beyond magnitude 17.5 to 18, the limit now apparently set by the target's ability to store images at room temperature. Cooling apparatus is planned. Aikens and Barton[2] have reported a $^3/_4$ magnitude gain with a 22°C drop in tube envelope temperature, while Livingston[3] reports high-quality image storage by very cold tubes for periods of two hours, both using tubes with MgO targets.

Resolution

Suppressing skylight in many instances will reveal a new problem, arising from the statistics of stellar distribution. If one attempted, for example, to use image orthicons on the Dearborn instrument to generate a star catalog extending to the 18th magnitude, he would find that "coincidence losses" would be severe over perhaps 20% of the sky, simply because the resolution element for faint stars encompasses some ten square seconds of arc. It is possible to match the orthicon resolution to that of the telescope by optical projection, but only by reducing the field to a width of three or four minutes of arc. Even though, as Bakos has commented, the standard image orthicon on a 12-in. (30.5-cm) Cassegrain systematically records in 8 sec all galaxies having discernible shape on the Palomar Atlas, the same image orthicon on the 48-in. (122-cm) Schmidt would not be the receiver of choice because the large size of its resolution elements would be the limiting factor and the orthicon's sensitivity would not be the asset it is on slower instruments. It is clear that many of the possibilities of the image orthicon cannot be realized unless at least an order of magnitude improvement is made in faint-image resolution.

Nonetheless the high sensitivity of the orthicon offers, in some instances, the possibility of using optical magnification and at the same time employing a much shorter exposure time than possible with fast emulsions. Figure 4 shows the appearance of Copernicus on the monitor screen at 30 frames per second; the prime focus image of the Dearborn 47-cm refractor has been enlarged about fifteen times to a $^1/_2$-in. (12-mm) circle on the orthicon photocathode. A still camera using Tri-X film photographed the P-4 monitor screen at $^1/_{15}$ sec, $f/4$. On movie film one can select frames and achieve still better results, although some questions can then be raised as to which features are real and which are the product of our atmosphere. At least with an 18.5in. (47-cm) refractor, and objects as bright as Jupiter and the moon, one is always able to equal the angular resolution attainable with direct photography and still employ exposures one tenth as long or less, although at the expense of a reduced field.

Related Devices

Because the resolution of the image orthicon falls off with increasing light intensity (for extended objects) and with increasing beam current (for any object) it is logical to propose intensifying the image seen at the photocathode.

This intensification has been attempted in the "intensifier orthicon," and the sensitivity has been raised to the level of quantum-limited operation. The coupling between the intensifier section (a single-stage intensifier of conventional form) and the image section, however, was accomplished simply by making a sandwich with the intensifier phosphor on one side of a thin mica sheet and a photocathode on the other; the loss

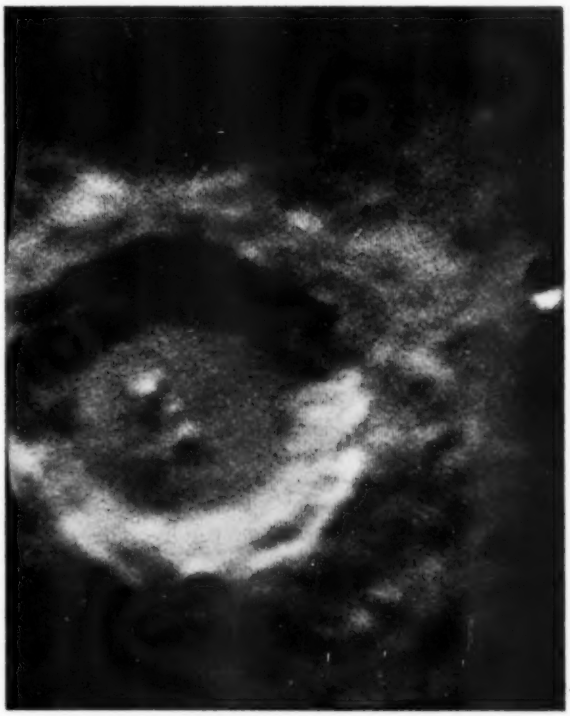


Fig. 4. Typical image of Copernicus as viewed at 30 frames per second on kinescope using eyepiece projection at focus of 18.5-in. (47-cm) refractor.

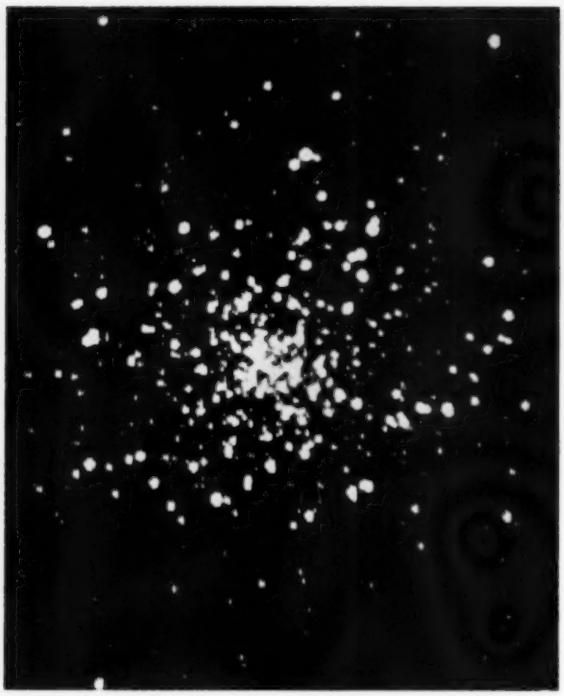


Fig. 5. M-13 in Hercules taken with Dearborn image orthicon system in 28 sec.

of resolution at this point due to omnidirectional radiation of light from the phosphor severely restricts the usefulness of the tube, despite its convenient one-envelope construction.[4,5] The development of fiber coupling is under investigation for tubes of this type, but nothing has yet been made available. At Dearborn we are investigating separate intensifiers optically coupled to the orthicon; we use a Rauland one-stage image tube (photon gain = 30, resolution = 80 lp/mm, 25-mm input and output) and $f/0.8$ coupling optics.

In many cases a gain in resolution would also result in a gain in sensitivity because a given stellar image would not be dissected into so many parts. The "field mesh" orthicon is a most interesting development which promises at least to double or triple the number of lines resolvable at low light intensities.[3] In this tube a mesh similar to the target mesh is added on the electron gun side of the target. Fields in the immediate vicinity of the target are kept more uniform, bending of the scanning beam near point images is substantially reduced, and in general many of the operating parameters of the tube are made less critical. These tubes are now available from several manufacturers, and may well entirely supplant the standard image orthicon in scientific work. It appears that with this tube, the theoretical resolution of the Dearborn telescope (0".25) would be realized (in a still atmosphere) with optical magnification of at most six times, and seeing-limited resolution (1" to 1".5) with no magnification at all (see Fig. 5).

In yet another variation, a standard image orthicon is fitted with several added electrodes to operate as an "image isocon." The added electrodes allow the scanning beam to be intercepted as it returns from the target; only those scanning electrons scattered by an encounter with a charged image element return all the way to the multiplier structure, and their number is proportional to the quantity of charge encountered. The polarity of the output signal is the reverse of that from an ordinary image orthicon; the output signal is least for the faintest images. This fact obviously means a far more favorable noise level than in the orthicon; in practice, signal-to-noise improvement over the orthicon mode of operation (possible in the same tube) is of the order of 10:1 or better at low light levels,[6] with comparable or better resolution.

One can only speculate as to the properties achievable by adding a field mesh to this tube! The chief drawbacks to the isocon are first the difficulty of achieving the correct operating mode, and second the fact that the number of electrodes, and hence external connections, is not standard, so that before one can test such a tube he must modify his equipment. Such considerations, however, cannot outweigh the attractive prospect of having the noise decrease as the signal decreases, instead of the opposite.

Reference 6 contains complete operating instructions for the isocon, as well as instructions for construction of the necessary adapters and voltage control circuitry, and a clear description of principles.

Conclusions

The theoretical limiting magnitude expressions developed in this paper relate various sources of tube noise, time, sky background, and over-all resolution to the limiting magnitude attainable in a single exposure. The concept "limit" in this application is defined in terms of signal-to-noise ratio, enabling probabilistic predictions to be made.

With estimated values of parameters a result of about 17th magnitude in a 16-sec exposure for an 18.5 in. (47-cm) telescope is obtained, which is close to observed performance at Dearborn.

The suppression of skylight has apparently been accomplished in wide-angle television photography; preliminary results indicate that this method will permit at least three times longer exposures than heretofore possible under moderately high background conditions.

Resolution obtainable with television techniques for some objects may be better than that obtainable with direct photography. Dearborn photographs of the moon show resolution of around $^1/_2$ sec of arc (estimated) on nights when the longer exposure required for film normally imposes a 1 to 3 sec seeing limit.

This paper is not intended as a review of all of television astronomy, but the paucity of publications seems to indicate a need for some explanations of orthicon operation and a brief survey of some devices that have been used in this area. The field-mesh orthicon, the image isocon, and various means of preintensification of images have been briefly discussed. To suggest possible applications of television astronomy to research workers who contemplate entering this field, we conclude with a short list; the following are projects that are now being carried out at the Dearborn Observatory.

1. Calibration of the orthicon as a photometer for point and extended objects; use as a skylight meter.
2. Monitoring of distant galaxies for supernovae.
3. Measurement of asteroid and faint satellite positions for orbital calculations (to better than 4″ accuracy); measurement of short rotation periods.
4. Measurement of faint, close double stars of short period.
5. Objective-prism spectroscopy and single-star spectroscopy (grating spectrograph under construction).
6. Comparison of direct photography with image orthicon photography.
7. Micro-albedo studies of selected areas of the moon; construction of moon pictures with enhanced contrast for reference during recording of attempts to land probes on the moon.
8. Extension of integration time by cooling and sky suppression.
9. Addition of continuously variable magnification for acquisition and tracking of moderately fast satellites and probes.
10. Coupling image intensifier(s) to orthicon.

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A Liquid Calorimeter for High-Energy Lasers

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At the outset of investigation of laser systems it was apparent that measurement of output energy is a problem requiring specialized techniques. Calorimetric methods were initially applied and have remained the primary means of measuring laser energy. In addition, several photosensitive and mechanical devices have been designed, and successful energy measurements have been reported.[1,2]

It has been demonstrated in practice that many of the solid absorber and thermopile instruments presently in use will not be satisfactory for measurements of the energy output predicted for future laser systems. Localized radiative cooling, blasting of minute particles from the absorbing surface, and consequent change of absorptivity present serious difficulties. Energy of 20 J or more can destroy calorimeters of the blackbody type.

Investigation of a calorimeter employing a different absorbing mechanism has been undertaken. It was predicted that a liquid absorption medium of proper specific heat would provide an excellent calorimeter for energy measurements in the visible and infrared wavelengths. If the energy absorption were distributed throughout a mass of liquid, the resulting temperature change would be a matter of a few degrees above ambient, instead of the several hundred degrees observed at the surface of a solid such as carbon.

The initial relative temperature distribution in a liquid medium is shown in Fig. 1. The two curves demonstrate the distribution for values of absorptivity of 98% and 80% per centimeter, respectively. Adjustment of path length and absorptivity permits a uniform temperature throughout the mass of liquid to be reached quickly by convection. The temperature change can be accurately measured to within a hundredth of a degree centigrade with a precision thermistor.

Since the lasers presently available for laboratory work have energy output of about 5 J, the calorimeter design was for this relatively low value. A sketch of the calorimeter in the form of an evacuated double-walled glass Dewar is shown in Fig. 2. Com-

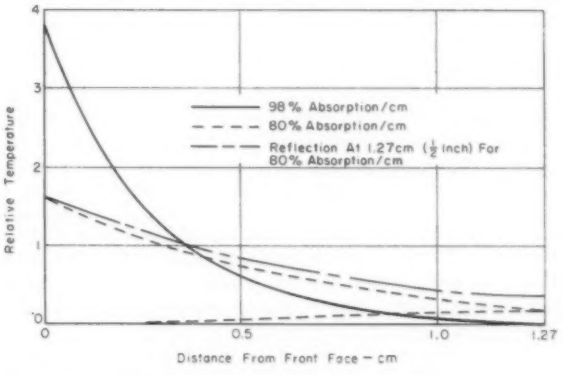

Fig. 1. Initial relative temperature distribution.

parable performance was achieved with a calorimeter consisting of a cavity drilled in a polystyrene block.

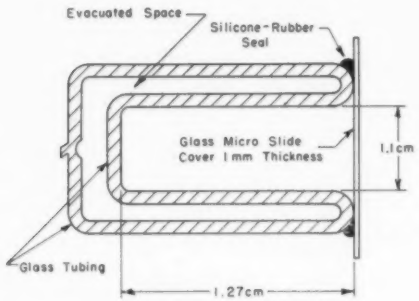

Fig. 2. Calorimeter.

A detailed analysis of the temperature change of the insulating materials surrounding the liquid was performed and an over-all heat capacity for the liquid and insulation was derived. The major source of heat loss is across the glass entrance window.

The temperature of the liquid in the calorimeter is monitored by a thermistor constituting one leg of a Wheatstone bridge. Use of a small thermistor bead assures excellent thermal contact; the additional heat capacity is negligible in comparison to that of the liquid. Precisely manufactured thermistors are available that permit design and calibration of the bridge without performing tests on individual thermistors.

Pulsed calorimetric measurements require accurate values for the sensitivity of the thermistors at all operating temperatures. Therefore, no attempts were made to compensate the bridge for ambient temperature variations. Instead, direct energy calibration of the bridge output is derived from the value of the bridge balance resistor and the heat capacity of the calorimeter. A precision potentiometer was used to balance an equal arm bridge at 10 kΩ as the ambient temperature varied.

Distilled water gave excellent temperature sensitivity for laser energy greater than a few tenths of a joule. At the reference temperature of 25°C, the 10 kΩ thermistor in an equal arm bridge gives an energy sensitivity of 5.06 J/mV, when immersed in the calorimeter. This figure varies by about 1% per degree if the ambient temperature varies. For final calibration this figure is modified by the over-all heat capacity.

The water was dyed with ordinary green recorder ink to an absorptivity of 80% per centimeter. The absorptivity was measured at the laser wavelength by means of a tungsten source, a narrow-band optical filter, and a phototube. The 80% curve of Fig. 1 includes the reflected energy from the back surface of the calorimeter cavity, the proper absorptivity being calculated for twice the cavity depth.

To provide a check on the cooling rate and calibration of the calorimeter, an identical cavity in a polystyrene block was constructed with a small resistance heater inside. Recordings were made of the thermistor bridge output and logarithmic plots were derived from the recordings. A typical plot is shown in Fig. 3. The log plots showed that the average cooling time constant is 120 sec. About 30 sec must be allowed for convection processes to bring about a uniform temperature distribution. Extrapolation of the bridge output back to the time origin gives an energy measurement close to the energy supplied by the heater. The average error in extrapolating is 5%.

Recordings were also made of numerous laser pulses into the calorimeter. The average value of the cooling time constant was the same as that derived from the heater tests. This indicated that the assumption of perfect insulating properties for short time periods for the evacuated dewar space is valid and that the principal cooling mechanism is across the entrance window. The cooling rate is such that measurements are repeatable at about 4 min intervals. Although better insulating properties would provide calorimetry measurements without the necessity of heat transfer loss calculations and an extrapolation process, this cooling rate permits practical repetition of energy measurements.

Operation of the calorimeter of the present design should be satisfactory for measurements up to 50 J, for which the temperature change would be only 10°C. However, it is desirable to keep the resistance change of the thermistor at small values for bridge measurements. Thus, more reliable operation is achieved if the temperature change is kept at about 1°C. Since the sensitivity of the thermistor bridge is very good, a high energy calorimeter designed for 50 J should cover a range of energy from 1 J to 100 J with a temperature range of 0.02° to 2°C.

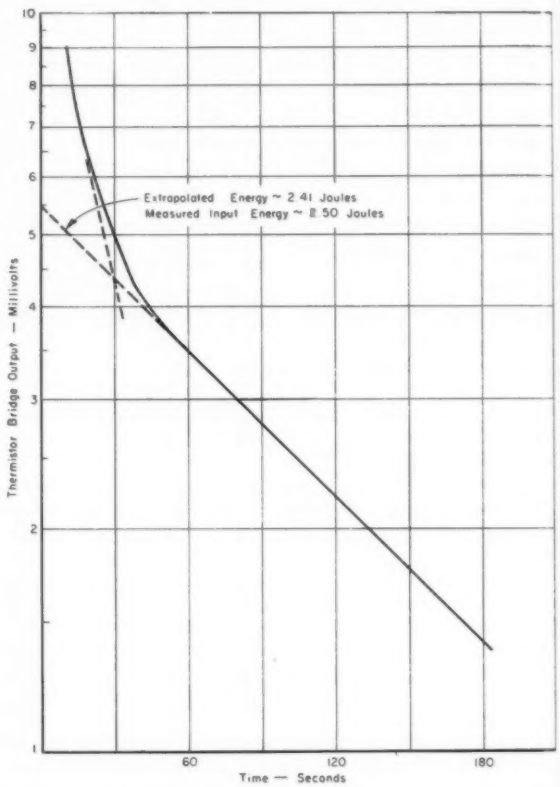

Fig. 3. Log plot of temperature recording.

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Letters *continued on page 175*

A Dual-Channel Pulse-Counting Astronomical Spectrophotometer

James P. Rodman

A spectrophotometer constructed and used by the author simultaneously compares 15 Å centered at Hα with 100 Å of flanking continuum, also 15 Å centered at Ca K with 100 Å of flanking continuum; the readout employs pulse-counting electronics and an automatic digital printer. Wavelengths other than Hα and CaK may be easily selected. Design criteria and relevant details of construction are discussed. A special cooling pump used to refrigerate the photomultiplier tubes is described, together with a system for preventing condensation of moisture on the optics and photomultiplier. The performance of the apparatus is discussed—in particular its approach to 1% accuracy in individual Hα line-intensity readings, and its ability to work through several magnitudes of varying clouds and extinction with essentially unimpaired accuracy.

I. Introduction

The spectrophotometer described in this report, constructed at the Yale Observatory over the past year and a half, was designed primarily to investigate the possibility of detecting and studying flares on stars other than the sun by sensing transient enhancements in flare-sensitive spectral lines. It is also being used to test the hypothesis that radio noise storms on Jupiter are caused by the dumping of numerous radiation-belt particles with consequent observable auroral activity. The flare-detection observations are just beginning, and first results of the Jovian auroral detection program will be reported elsewhere. This article is concerned with design parameters and with the apparatus itself.

It is clear that if a class of stellar flares exists which is similar in nature and intrinsic luminosity to solar flares, such flares can be most readily detected on cooler dwarf stars of late spectral class (see ref. 1, Table IV). In the narrow spectral bands which must be employed for this work, the arriving photon flux from such stars is so small that the highest efficiency in the collection and utilization of incoming photon information is required. Ideally, an instrument of this type should:

1. Be used with a device providing maximum available light-collecting aperture,
2. Incorporate a wavelength-selecting device, have high over-all efficiency at the wavelengths to be observed, and have adjustable output bandwidth,
3. Be as free as possible from all types of instrumental drifts and variations, and have a means for compensating such drifts as may occur (subject to any limitation imposed by this requirement, the instrument should also make use of the maximum possible fraction of each observing period for the collection of useful information),
4. Be automatically compensated for extinction including clouds,
5. Provide output data in a form easy to process, including an easily adjustable integration time,
6. Be designed as far as possible to be generally useful for other purposes without impairing its suitability for flare detection.

The wavelength-selectivity requirement suggests that the apparatus be either some form of spectrograph or a band-pass filter device. In the latter case, the narrowness of the required output bandwidth permits only interference filters to be used. The need for high over-all efficiency requires that the prime detector have the highest available total quantum efficiency; prime detectors best satisfying this requirement, at least for low light levels, are selected photomultiplier tubes using pulse-counting output electronics.

Unfortunately, the slight (and thus far not fully understood) time-dependent internal sensitivity variations in photomultipliers (see, e.g., ref. 2), which with the cells we have used are of the order of a percent over periods of an hour, are apparently inherent in the tubes and not readily subject to outside control. Pulse-counting electronics should be less subject to

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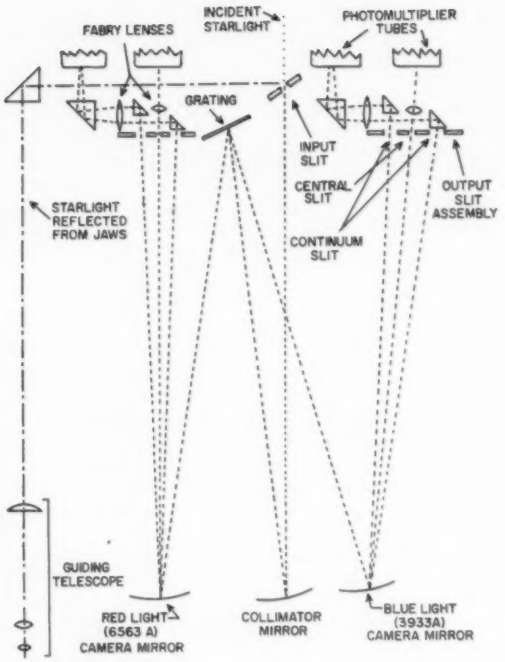

Fig. 1. Spectrophotometer optical layout.

error due to drift than the electronics involved in direct-current techniques, as the effects of any slight drifts which do occur with pulse-counting circuits can be minimized by causing the photomultipliers to operate as nearly as possible on the "flat" portion of their output curves where essentially all photoelectron-originated pulses are counted. Variations caused by image wandering over a nonuniformly-sensitive photocathode can be minimized by appropriate Fabry optics, while significant wavelength shifts due to spectrograph flexure should not be present in proper mechanical designs.

One might compensate for drift by adopting a single photomultiplier as the detection element, alternately scanning first the flare-sensitive line and then the adjacent continuum, the switching rate being much shorter than the periods of the expected or observed flare-induced fluctuations or instrumental drift. This method, while almost totally eliminating drift, discards at least 50% of the incident information. Alternatively, one might consider two photomultipliers, one looking at the continuum and the other at the spectral line; ideally, this system is capable of using 100% of the incident information, but provides no compensation for drift in the two phototubes. In practice, necessary compensation can be introduced through a switching process at some cost in observing efficiency. Atmospheric transparency compensation is desirable in the East in order to maximize the amount of observing time. This may be achieved to the first order by using two photocells to observe simultaneously both the flare-sensitive line and a pair of continuum regions equally spaced on each side of the line.

The statistical detection threshold for flares varies with the square root of the integration time. In pulse-counting methods, a change in integration is effected by merely turning on the pulse-counting registration for whatever period is desired, resetting the counters, and repeating the run; this can be done automatically by suitable electronic circuitry. It is normally easier to process digital information statistically; and pulse-counting can give digital information directly on punch-tape or cards suitable for immediate analysis with high-speed digital computers.

The criterion of flexibility also suggests choice of a spectrograph design which is readily adaptable to other uses such as the determination of equivalent widths.

The design criteria considered led to the following design choice:

A photoelectric spectrophotometer employing a modified Czerny-Turner construction and pulse-counting output, with paper-tape printout and automatic recycling, seeing compensation, and internal wavelength sources. In addition, this spectrophotometer is arranged for simultaneous observation of a second flare-sensitive line and its adjacent continuum, and is incidentally adaptable to photographic spectroscopy.

II. The Spectrophotometer

Rather severe limitations on possible designs for the spectrophotometer were imposed by requiring it to fit on the 51-cm $f/15$ Cassegrain reflector at Yale. This reflector was in part constructed with components from a precision siderostat originally used with the Yale Observatory 15.2-m Loomis refractor before the latter was permanently converted to a fixed polar telescope. As a result the new reflector has very little clearance between the back of the mirror cell and the fork of the mounting, forcing the spectrograph to be contained in a flat, rectangular space of dimensions 112 by 43 by 15 cm.

The modified Czerny-Turner optical design is shown in Fig. 1. Light entering the input slit is reflected by the collimator onto a plane reflection grating, which can be rotated to send a desired wavelength to the principal (red-light) camera mirror. The principal output slit assembly consists of a central aperture which permits radiation to reach one photomultiplier tube directly; a pair of flanking output slits feed the light through several prisms to a second phototube. The spectral line one wishes to study is placed in the central slit, its width determining the passband of the radiation. Light from the adjacent continuum reaching the

second photomultiplier will have amplitude variations proportional to those occurring at the central wavelength unless a true line enhancement occurs in the source. The ratio of central intensity to adjacent continuum thus becomes the flare-sensitive criterion. The auxiliary (blue-light) camera mirror is part of a second output system where another line-versus-continuum ratio can be simultaneously studied.

Figure 2 shows the spectrophotometer, constructed of 12.7 mm aluminum jig-plate, in an inverted position with cover removed (this figure suffered a right-to-left inversion during reproduction, but the inversion will not hamper understanding of the construction). The prominent square white object near the center is the diffraction grating. A tangent arm extending to the left from the bottom of the grating cell terminates at the head of the wavelength-adjusting micrometer, which also appears white. This micrometer is rigidly mounted to the sub-baseplate which holds the grating assembly, in order to minimize unwanted wavelength changes due to mechanical flexure. The two mirror-surfaced circles to the left and the right of the grating contain the output slits used during first observations with the instrument at the Kitt Peak National Optical Observatory; the slits themselves appear as small black rectangles near the centers of the circles. Miniature blackened porcelain sockets near the slits contain hooded lamps designed to illuminate faintly the output slits during calibration and wavelength checks. The input slit assembly, minus its enclosing box, is just to the right of the grating. The wedge-shaped sector

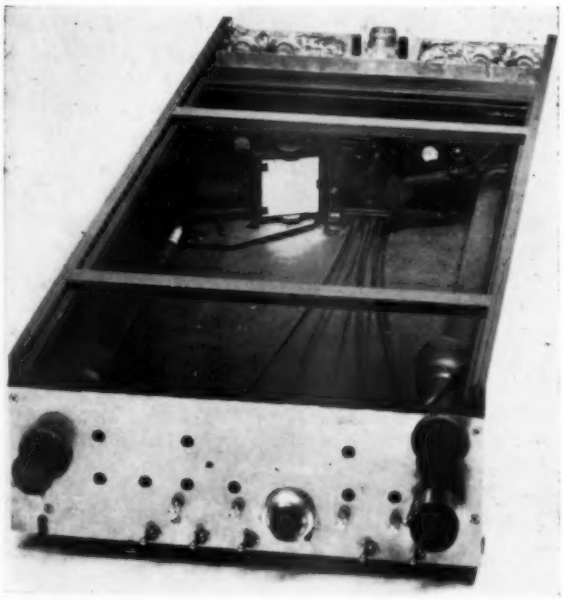

Fig. 2. View of controls, and of slit and grating end of the spectrophotometer.

mounted behind the block where the control rods terminate is used to exclude light during dark counts. Incident light reflected from the inclined polished input-slit jaws, passing through the inclined housing to the right, is prism-reflected down the tube at the extreme right to the guiding telescope whose eyepiece, which contains illuminated crosshairs, can be identified on the control panel by a circumferential bright band. The thin rod which touches this eyepiece on the left focuses the guiding telescope by moving the objective of the telescope longitudinally. Immediately above the eyepiece of the viewing telescope can be seen the eyepiece of one of the telescopes focused on the output slit; the companion telescope for the other slit is on the left of the control panel. Below the eyepiece of this latter telescope is the knob whose rotation selects the output wavelength, read directly in angstroms on a counter visible through the U-shaped slot directly below. Bat-handle toggle switches control the neon and argon spectrum glow lamps, the intensity calibration lamp, the output slit illuminating lamps, and high voltage to the photomultiplier tubes. As a precaution directed toward preserving the sensitivities of the photomultiplier cathodes, the switches which turn on the spectrum lamps simultaneously turn off high voltage to the phototubes. Four small shiny knobs above the switches introduce and remove the spectrum-comparison prism and the cross-slit from the optical train, actuate the dark shutter, and select the proper comparison lamp. The duodial in line with this row of knobs adjusts the width of the input slit. Immediately above are nine dark apertures, normally closed with light-tight tape, through which one inserts a special wrench to adjust the positions of the collimator and camera mirrors. At the extreme rear end of the spectrophotometer a brass tray contains four cathode followers used to match the output impedances of the photomultipliers to the coaxial cables carrying the signals to the pulse-counting electronics.

Figure 3 shows at the other end of the spectrophotometer the collimator mirror and the two flanking camera mirrors. Also visible within the spectrophotometer body is an assembly containing the class VII precision ball bearing supporting one end of the pivotal axis attached to the grating housing. The electronics tray and beaded styrefoam insulation normally present here have been removed to reveal the copper enclosures containing the photomultiplier tubes. These enclosures are secured to the side of the spectrophotometer case by stiff rods, made of micarta for heat-insulation purposes. Also shown is an exploded-type representation of a photomultiplier tube and its socket, together with a mu-metal shield and the airtight end cap which seals these components in the photomultiplier enclosures. Automobile window channels pressed into the aluminum sides of the spectrophotometer provide a

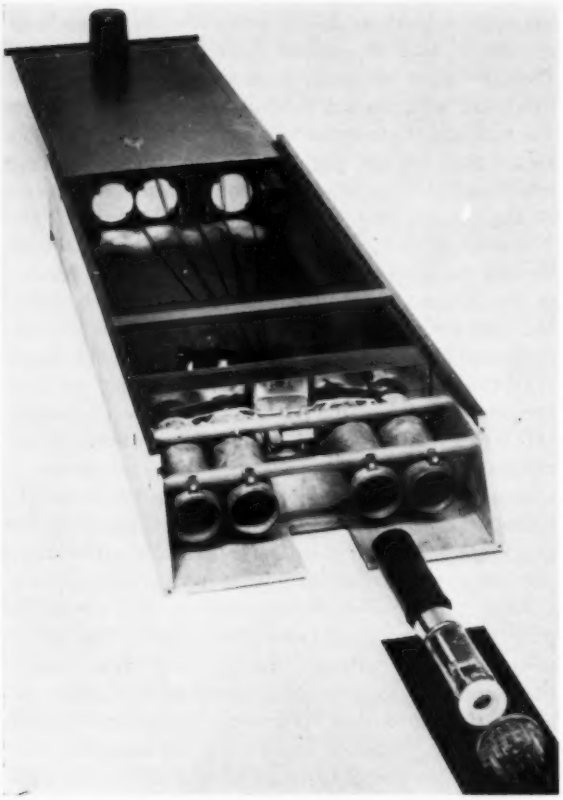

Fig. 3. View of photocell mountings, and of collimator-camera end of the spectrophotometer.

light-tight seal for the formica sliding cover (seen here in the open position), on which a desiccant chamber for indicator-type silica gel is mounted.

The input slit assembly is shown in Fig. 4. The opening of the polished stainless steel slit jaws is controlled by the small taper-spindle micrometer, rotated by a gear-and-shaft system from outside the spectrophotometer. Movement of the star image along the slit, and hence wandering of the final images on the photocathodes, are restricted by a cross-slit made of two pieces of aluminized thin glass; a knob on the control panel removes the cross-slit from the optical train during wavelength calibrations. The input slit assembly also includes socket-mounted argon and neon lamps used during wavelength calibrations, and a tungsten lamp used for intensity calibrations. A subassembly holding these lamps is moved along a track by a rack-and-pinion drive so the desired lamp can be caused to illuminate the slit. The larger crank handle seen in Fig. 4 turns the comparison-spectrum prism in and out of the optical path. Both this element and the cross-slit are spring-loaded against stops in the "in" position, since the use of crank-handle linkages for the removal only of these elements precludes the serious damage which might result if they were forced against the "in"-position stops. Not visible is a plane diagonal mirror, mounted on the spectrometer side of the slit, which introduces the 90° reflection necessary to render the input light parallel to the flat base of the spectrophotometer.

The collimator and camera mirrors are 76-mm diam $f/10$ spherical mirrors, and the adjustable backing plates on which they are mounted are connected to the spectrophotometer base plate by three-point right-triangle-located screw- and push-spring assemblies which allow for focusing and collimation.

A moderately high linear dispersion of 10 Å/mm was selected in order to permit the use of relatively large output slits, for which errors caused by dirt or nonparallelism of output slit jaws tend to be less than with narrower slits. This dispersion was achieved with a Bausch & Lomb plane reflecting replica grating of 1200 lines/mm, blazed for 5000 Å in the first order, and of adequate size (68 × 68 mm) to intercept totally the incident beam of parallel light from the collimator. Grating-rotation selection of output wavelength follows from a tangent-arm micrometer-ball drive somewhat like that used by Badger *et al.*,[3] where the relation between micrometer rotation and wavelength change is linear. The length of the tangent-arm was adjusted so that a mechanical counter geared to the micrometer drive indicates, directly in angstroms with an accuracy of about ±2 Å, the output wavelength at the principal

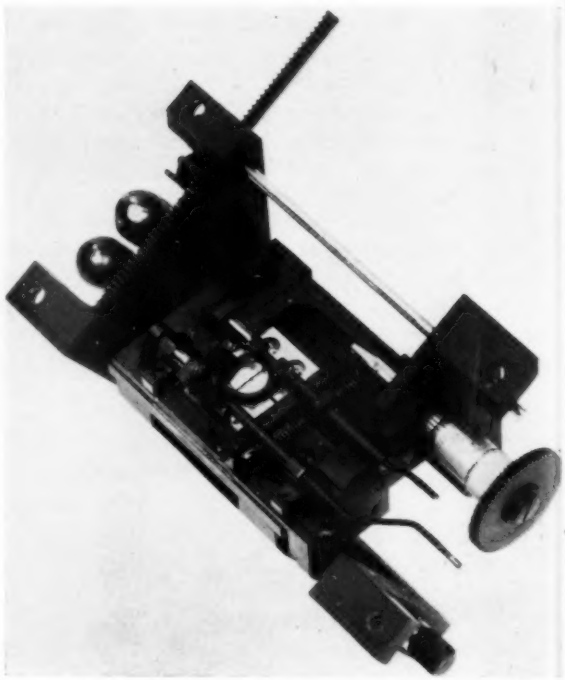

Fig. 4. Input-slit and calibrating-light assembly.

output slit. The knob which is rotated to change the wavelength is equipped with mechanical stops which make it possible to shift wavelength by a preset 20 Å to permit compensation for photomultiplier drifts by a method described below.

The two camera mirrors of the spectrophotometer simultaneously focus two regions of the spectrum onto separate output slit assemblies. Since these two optical channels are identical, a description of one will suffice. The output slits originally used on the instrument and illustrated in Fig. 2 were made from selected microscope slides, totally aluminized except for three small rectangular apertures, which are the central and comparison slits. Aluminum was prevented from being deposited over the slit areas by three small blocks of tool steel, accurately machined to the desired slit dimensions, placed at the slit positions prior to aluminizing. Following aluminization, the steel blocks were removed magnetically, leaving sharply defined slits on the surfaces of the slides. The widths of the slits correspond to the desired output bandwidths, but the heights were made greater than the cross-slit-determined height of the input slit to insure that excursions of the star along the input slit cannot cause the light to be cut off by the top or bottom of the output slits. If such cutoff occurred and was not exactly matched in the adjacent slits, the apparent variation in the resulting line-versus-continuum ratio would be difficult to disentangle from true flare-induced variation. The mirror surfaces on the remaining areas of the output slides serve to reflect spectral calibration lines into viewing telescopes. Although this type of output slit is usable, it adds two glass reflecting surfaces with their associated losses to the optical train. An even more serious objection is that localized dirt on either of the surfaces will also produce line-versus-continuum variations of the type described above.

The slits currently used on the spectrophotometer are formed from stainless steel knife-edges rigidly mounted on an aluminum backing plate, which is precision-milled to position accurately the knife-edges. At present a 15 Å central passband is flanked by two opaque sections each 40 Å long, then by the continuum slits each having a 50 Å passband. Such an arrangement provides linear compensation for errors which would otherwise be introduced by wavelength-dependent atmospheric scattering and which might be misinterpreted as flares. Tests have demonstrated that this spectrophotometer with the double-comparison slit arrangement as described gives line/comparison ratios which are not detectably affected by up to four magnitudes of cloud-induced extinction (except, of course, for increased statistical scatter resulting from decreased photon flux). In other words, when dealing with relatively bright objects, the system may be used under any sky conditions short of solid overcast.

The continuum slits have been made about an order of magnitude wider than the central slit in order that, for equally sensitive photomultipliers, the faint-source detection threshold determined by statistical fluctuations will be set largely by the amount of light entering the central slit. It is also important to note that a shift in output wavelength of 20 Å displaces flare-sensitive spectral-line information previously entering the central slit onto one of the opaque sections, thus permitting continuum-versus-continuum observations (presumed flare-insensitive) to establish a baseline to which the line-versus-continuum variations can be referred. Photomultiplier sensitivity drifts should appear to an equal degree in each of these ratios, and can therefore be removed from the output data.

First-surface strip mirrors 20 mm long mounted above and below the slits reflect calibrating spectra into the output slit viewing telescopes. During calibration, light-tight telescope eyepiece caps are removed and the slit apertures are dimly illuminated by means of red-dyed No. 328 aircraft lamps located behind the slits and run at 18 instead of their rated 28 V.

Conventional Fabry lenses, located close behind the output slits, image the camera mirror of each channel on the photocathodes. This system of imaging was introduced after tests of the spectrophotometer at Kitt Peak showed that attempts to circumvent scintillation fluctuations by imaging the output slit on the photosurfaces introduced noncontrollable errors of several percent because of the wandering of the spot over the nonuniform photocathode. It was hoped that the use of an extremely small-diameter spot ($^1/_2$ mm) and the limitation of its excursions to less than one spot diameter would enable one to select a uniform section of the photocathode, but such proved not to be the case. Subsequent investigations of the photosensitivity of the cathode with a very small (0.25-mm) spot revealed that irregularities of several percent exist even in these small areas. The present system suffers in that input image drifts and scintillation patterns caused by the turbulent atmosphere are imaged on the photocathode[4]; however, integration times on the order of a minute or even less strongly tend to average out these variations.

Photomultiplier tubes used in astronomy are often cooled to reduce the intrinsic thermal dark currents, particularly when one is working with faint sources. Usual cooling methods, which often involve an insulating material enclosing both the phototube and a surrounding dry ice chamber, could not be used in this spectrometer because of the very limited space available in the vicinity of the phototubes. Figure 5 illustrates the system used instead. Dry ice, introduced through a port in the top of the apparatus, serves to cool a supply of methanol in the reservoir

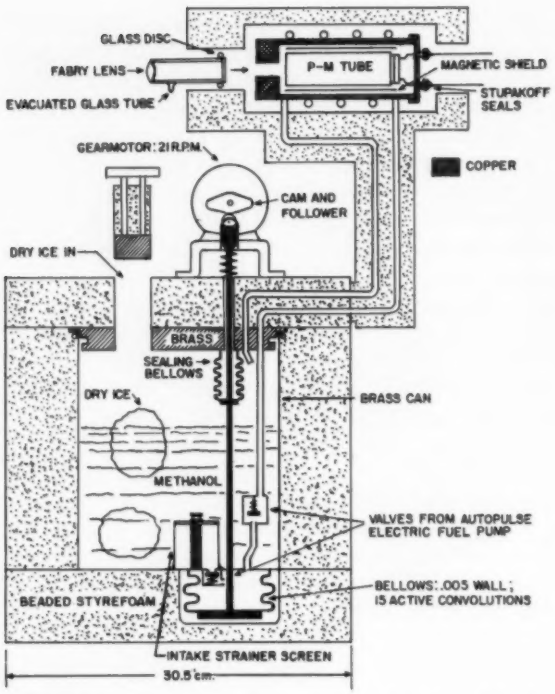

Fig. 5. Photomultiplier cooling system, using pumped dry-ice-cooled methanol. Cooling system: the diameter of the unit is about 30 cm.

chamber. The cold methanol, filtered free of pieces of dry ice by an input strainer screen, enters a bellows-bodied force pump and is circulated through passages in the airtight copper chambers which enclose the photomultiplier tubes. The end-windows of the phototubes, internally coated with the photocathode material, are very lightly spring-loaded into direct contact with the ends of their respective chambers, insuring maximum cooling. Such an arrangement, easily effected in pulse-counting work where the cathode can be set equal to ground potential, is ruled out whenever a high cathode-to-chamber potential exists, as the resultant potential gradient between the chamber and the photosurface appears to increase tube noise sharply. The temperature of the copper enclosing chamber, measured with a Leeds and Northrup temperature potentiometer and thermocouple, is assumed to equal the cathode temperature. Experience shows that the temperature of the tube chambers can be accurately controlled to $\pm 1°C$. The system can be cooled to -66°C in forty-five minutes from an ambient temperature of $+20°C$.

Considerable care has been taken to avoid unwanted condensations. Over-all heat insulation is achieved by completely embedding the copper enclosure chambers in machined close-fitting beaded styrefoam. The phototubes, plugged into their standard sockets and enclosed in mu-metal magnetic shields, fit snugly in their hermetically sealed chambers (to exclude moisture which would otherwise freeze out on the tubes). Dynode leads from the socket pins are individually brought out through the chamber end-plate by individual kovar-to-glass Stupakoff seals, whose 38 mm long glass bodies pass through styrefoam insulating blocks to the external dessicated chambers containing the voltage dividing resistors. Heat conduction in through the leads is minimized by the use of small-diameter copper wires, which are exposed to the atmosphere of the cold enclosures before reaching the tube sockets. At the other end of the cells, heat transport through the optical windows by both conduction and convection is minimized by forcing the light in passing through the styrefoam insulating block to go through 15-mm diam evacuated pyrex glass tubes 33 mm long. A Fabry lens, located immediately behind the central slit, is sealed to one end of the glass tube with epoxy cement; a similarly cemented plane glass window seals the photomultiplier end of the tube. Prior to installation, each glass tube assembly was evacuated through a small side tubulation with a diffusion pump and cold trap apparatus and checked for leaks with a helium mass-spectrometer before the tubulation was sealed off. The light reaching the continuum phototube passes through a similar glass tube, both ends of which are sealed with flat glass windows, as the Fabry lens in this case is located nearer the slit (see Fig. 1). The warm ends of these small glass chambers, placed in close proximity to the thick aluminum blocks which support the output slits, assume the ambient temperature of the spectrograph, and no evidence of window-frosting has yet been detected.

The photomultiplier tubes currently used in the spectrophotometer were selected after investigations indicated their suitability for this application. The S-20 photoemissive surface, because of its order-of-magnitude higher quantum efficiency at 6500 Å than other coatings commercially available, was chosen for the Hα channels despite the fact that this particular trialkali coating is often plagued by high dark currents which limit the ability of the spectrophotometer to detect extremely faint objects. The present Hα cells are EMI type 9558A, specially selected by the company for high cathode-luminous-efficiency at red wavelengths while having room-temperature dark currents of 0.001 μA or less. Tests of such tubes at Yale to determine their suitability for use in the spectrophotometer have shown that, while the manufacturer's sensitivity ratings are accurate and useful, dc dark-current ratings supplied by the manufacturer for individual tubes give little indication of pulse-counting dark currents at low temperatures. An apparatus constructed by

the author[5] permits photomultipliers to be tested for most of the factors important in astronomical pulse-counting applications. One may observe quantitatively the changes in response of the tube as applied voltage, ambient temperature, wavelength of illumination, and discriminator settings are varied. The apparatus may also be used to make detailed plots of the over-all luminous sensitivity of the tube as a function of the position of a spot of light projected onto the face of the tube.

EMI type 9502S and 6256SA tubes were investigated for use at the wavelength of the auxiliary channel, at present set on the CaK line (3933 Å). These tubes possess small photocathodes (10-mm diam, compared with the 50-mm diam cathodes of the 9558A tubes). An intrinsically quiet antimony-cesium cathode, which at 4000 Å has as high a photon efficiency as the 9558A, yields a refrigerated pulse-counted dark current of only about 2 pulses/sec, an order of magnitude less than the dark current of type 9558A.

We find[5] that the dark current has both thermal and nonthermal components. Typically, cooling a type 9558A phototube from +30° to +20°C reduces the dark current by an order of magnitude, but the tube must be cooled a full 40°C beyond this to gain a further factor-of-ten reduction. Over the range from −20° or −30°C down to −70°C, the dark current consistently increases slightly with temperature. Our tests indicate that this residual nonthermal dark current is not external leakage but rather is a function of the type of cathode and of the individual cell (the better type 9558A tubes have between 10 and 30 dark counts/sec). Unfortunately this nonthermal component is decidedly nonstatistical in nature, with characteristics differing for each cell, but exhibiting a standard deviation in the integrated counts ranging in our tests from 1.5 to 4 times that to be expected from the total number of pulses if these were truly random. Such tubes obviously have poorer detection thresholds than tubes with statistical dark currents.*

Several other sources of undesirable photomultiplier-associated variations must also be considered. Young[6] states that temperature changes may be accompanied by sensitivity changes in photomultipliers. Our investigations show that temperature changes of as much as ±3°C do not appear to affect our apparatus, and since our method of cooling will give a stability of ±1°C, such sensitivity changes do not appear to present a problem. In any case, our method of reducing data removes virtually all traces of these sensitivity drifts. High voltage is furnished to the photomultiplier tubes by a Hamner Model N4035 regulated high-voltage supply which is in turn fed by a Sorensen Model 5000S 0.1% line-voltage stabilizer. A Hycon Model 615AR digital vacuum-tube voltmeter constantly monitors the output voltage, which is stable to 0.25% or better. Such a supply is more than sufficiently drift-free for pulse-counting work, and voltage-induced fluctuations have not been observed. Cross-talk interference among the tubes is eliminated by individual L-section decoupling filters consisting of 100,000-Ω resistors and 0.01-μF Glassmike capacitors. The dynode voltage dividers consist of 100,000-Ω (±10%) 1/2-W Allen Bradley (Ohmite) composition resistors, enclosed within desiccated chambers; precision resistors were deemed unnecessary because thermally induced resistance changes in a divider using identical resistors will not affect dynode voltages to at least the first order. The load resistors are 47,000, Ω and the coupling capacitors are 0.005 μF 2500 working volt Sprague mica condensers, which appear to have vanishingly small leakage currents (also, these capacitors are carefully cleaned with methanol prior to installation).

Figure 6 is a block diagram giving the interconnection of the various electronic components we currently use for pulse-counting, while Fig. 7 shows all units except the digital VTVM and the Sorensen stabilizer. Pulse-type cathode followers mounted directly in the spectrophotometer act as impedance transformers, matching the high-impedance photomultiplier outputs to the low-impedance RG 59 U coaxial cables which connect the spectrophotometer to the remainder of the pulse-counting electronics. Hamner N371 linear amplifiers were factory-modified to accept frequencies as high as 100 kc/sec at a slight expense (approximately 2%)

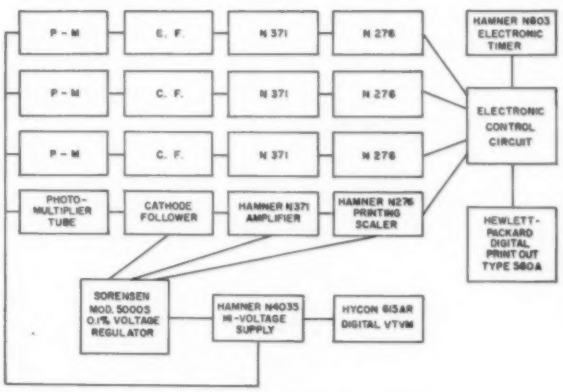

Fig. 6. Electrical block diagram.

* Jelley (private communication) suggests that, for very low light levels corresponding to slow true-count rates, the time constant of the pulse-counting apparatus can be made long enough to discriminate strongly against the multicount character of the nonstatistical burst-type components of the dark emission, while still counting almost all of the randomly arriving photons due to incident light. Thus the nonstatistical dark current can be made to appear more nearly statistical, and the detection threshold might be improved by as much as an order of magnitude.

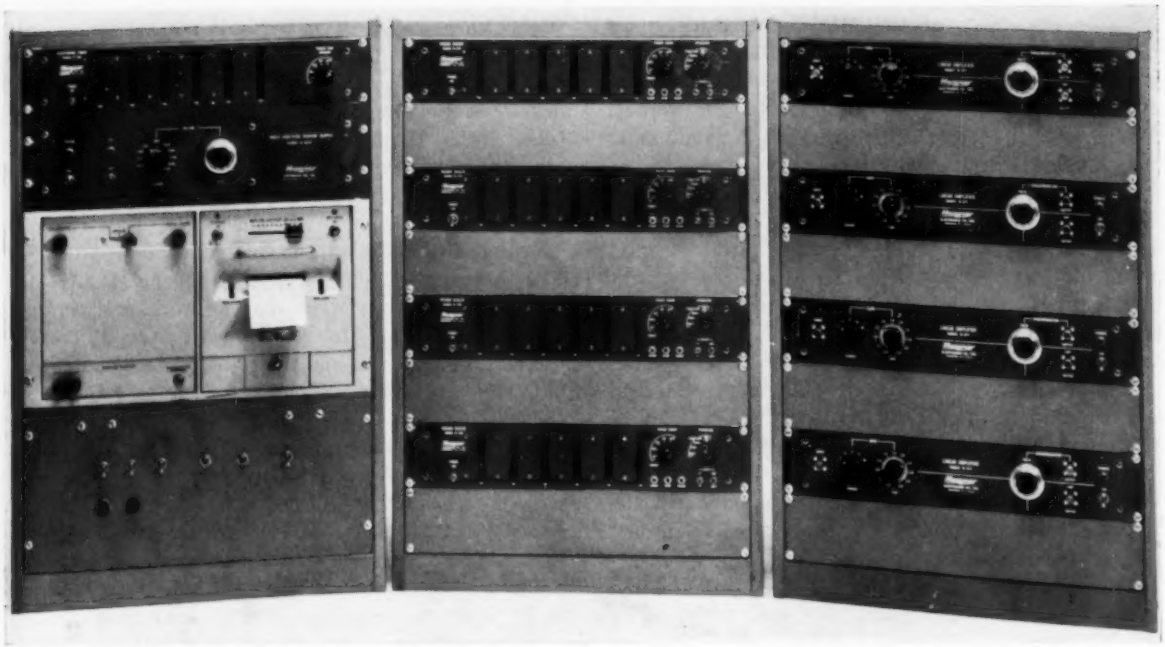

Fig. 7. Layout of complete four-channel pulse-counting, timing, and automatic printout equipment.

in linearity. Such nonlinearity, intolerable in dc techniques, produces no significant undesirable effect in our pulse-counting systems, as we operate close to the total-acceptance mode rather than in the proportional-counting mode. These amplifiers incorporate discriminators which we set to pass 90% or more of all light-induced pulses while rejecting spurious pulses originating in spontaneous dynode emission, in very small amounts of irreducible high-voltage leakage, or in sparks made when relay contacts close. The amplifiers are run at their maximum gain of 7000, which is just sufficient to amplify pulses originating in 11-stage 2000-V photomultipliers with cesium-antimony dynode surfaces to a level sufficient to trigger the N 276 Hamner printing scalers which they feed. The discriminators may be set higher for the 9502S and the 6256SA tubes than for the 9558A tubes because of the additional gain derived from 13-stage dynode chains; this is desirable as extra insurance against spurious pulses which would produce a proportionally greater effect on the much smaller dark currents characteristic of these tubes. The N 276 scalers have a maximum counting rate of 1 Mc/sec, comfortably in excess of the frequency response of our amplifiers, and provide staircase voltages proportional to the readings displayed by the individual decades. These voltages are sensed by the Hewlett-Packard Model 560 A digital recorder, which prints out digits corresponding to the individual decade readings. A Hamner Model N 803 crystal-controlled electronic clock is connected to a master control circuit designed by the author and described in Appendix A. This circuit causes the recorder to print out the data from all four scalers, then resets and restarts them for the next integration period.

Table I. Sample of Typical Spectrophotometer Output Data[a]

Photomultiplier tube EMI Type	Photomultiplier tube Serial No.	Channel	Bandwidth (Å)	Average[b] dark counts	Observed[b] standard deviation	Expected[b] standard deviation	Maximum[c] light-plus-dark counts
9502S	5598	Blue continuum	100	283	23	17	29974
6256SA	11519	CaK	15	106	11	10	9142
9558A	5844	Red continuum	100	170	14	13	61240
9558A	5833	Hα	15	1419	134	38	74571

[a] All data given for 50-sec integration periods.
[b] Averages over 20 successive integration periods, with $T = 65°C$.
[c] On β Lacerta (KO) apparent magnitude 4.58.

The entire printout and restart cycle for all four scalers is completed in 3 sec. Details of the photomultiplier voltage divider and cathode follower circuits also appear in Appendix A. The Sorensen Model 5000S line voltage stabilizer frees all of the above equipment from most of the effects of line voltage variations.

III. Construction and Operation

The spectrophotometer was designed and most of the construction was completed at the Yale Observatory over an eight-month period beginning in March 1961. The Kitt Peak National Observatory kindly granted observing time on its 91-cm reflector to the author, who transported the nearly finished apparatus to the Kitt Peak Observatory headquarters in Tucson, Arizona, in early November 1961. Leaning heavily on headquarters facilities made available by the Kitt Peak staff, the author completed and tested the spectrophotometer and associated electronic components in December, after which it was taken to the Kitt Peak mountain observing station where ten nights were made available for the author's use. Observations were made of test stars and nearby late-type main-sequence stars, principally ϵ Eridani, using EMI type 9558C photomultipliers (a low-sensitivity version of the 9558 tubes). Unfortunately, compensation was not undertaken to offset the subsequently discovered drifts present in the photomultiplier tubes. Also, the presence of nonuniformity in the photocathode over very small areas rendered unsatisfactory the then-used system of Fabry-imaging the output slit. While it is thus difficult to disentangle any flare-induced from instrumental variations in the Kitt Peak data, the observing period at Kitt Peak afforded an opportunity to test the entire apparatus on an excellent telescope under good observing conditions, and the improvements of equipment and technique subsequently carried out could scarcely have been made without the benefit of such careful preliminary observations.

Extensive photomultiplier tests were carried out at Yale through the spring of 1962, while improvements already described were being made in the spectrophotometer and the telescope was being completed. Observations began with the spectrophotometer on the new Yale Observatory 51-cm reflector in late July 1962. The apparatus works essentially as designed, in particular regarding independence of clouds short of overcast; however apparent relative sensitivity drifts between cells have made frequent drift-compensation readings a necessity. Some indicative data concerning performance of the apparatus are given in Table I.

The probable error of individual line/continuum ratio readings so far has not been better than 1%, even after compensation for drift has been applied and with use of integration times sufficient to build counts well into the hundreds of thousands where individual photon statistics contribute little scatter. With our 51-cm reflector and present photocells, and using one-minute integration time, a 6th magnitude star has Hα photon-count statistics also at the 1% uncertainty level. Since most of the contemplated program on stellar flares must be with fainter stars, for this work the residual instrumental errors are negligible. However, for work on brighter stars, for the planetary auroral program, and for possible work with solar flares seen by sky or planet-light, it would still be desirable, if difficult, to improve the individual reading stability. This instrument was designed independently of, but has significant features in common with the spectrophotometer of Griffin and Redman.[7]

The author wishes to express his appreciation to Harlan J. Smith of the Yale Observatory for his many contributions in connection with the planning, design, and use of this spectrophotometer.

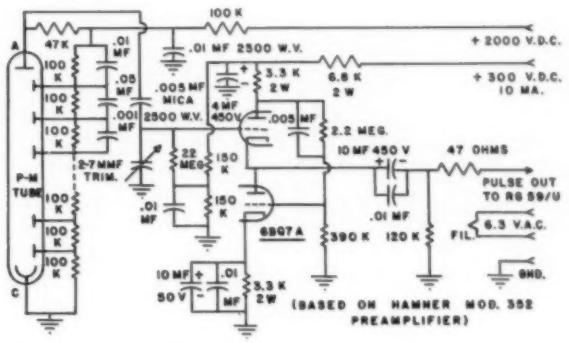

Fig. 8. Photomultiplier voltage-supply and cathode-follower circuits.

Appendix

A. The Photomultiplier Voltage Divider and Cathode Follower

Figure 8 shows the voltage divider and cathode follower circuits used with the photomultipliers in the spectrophotometer. A conventional dynode voltage divider, fed through an L-section decoupling filter, is composed of 100,000-Ω resistors capacitively bypassed near the anode end to help maintain linearity with large pulse amplitudes, although for the total-acceptance mode in which we operate such bypassing is almost unnecessary. The coupling capacitor located between the photomultiplier anode and the input grid of the cathode follower must be of the highest quality, in order to prevent electrical leakage. Sprague 0.005 μF 2500 working-volt 5000 test-volt capacitors appear

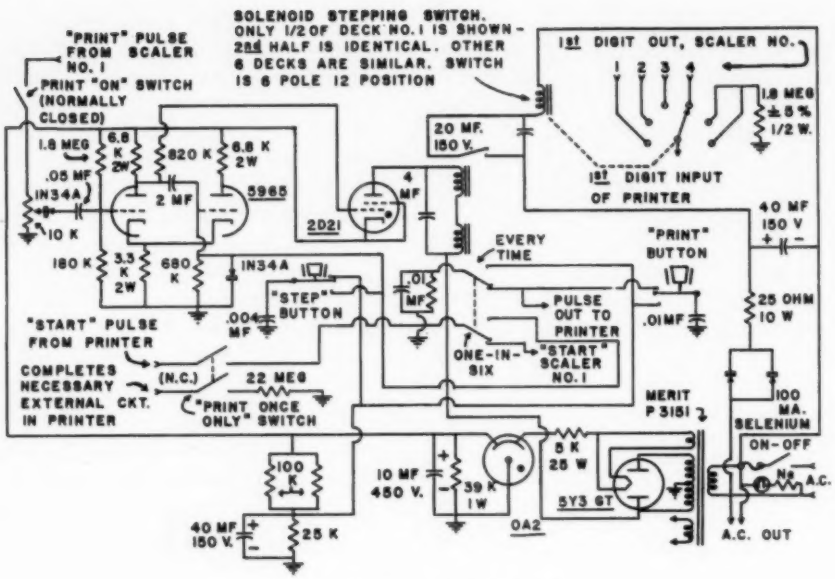

Fig. 9. Electronic control circuit.

to satisfy this requirement. The cathode followers are White-circuit type,[8] constructed in accordance with a diagram furnished by Hamner.* A 47-Ω resistor is inserted in series with the output for impedance-matching purposes.

B. The Electronic Control Circuit

In order to understand fully the operation of this circuit (Fig. 9), the reader should first familiarize himself with the theory-of-operation sections of the Hewlett-Packard 560A Digital Recorder Instruction Manual, but the basic principles of the electronic control circuit can be understood without this background. A description of a typical operating cycle follows.

At the conclusion of a counting (or integrating) period, the N 803 electronic timer sends a pulse to the N 276 scalers, causing them to stop. A negative print-command pulse originating in scaler No. 1 is received at the left-hand grid of the 5965 twin triode in the electronic control circuit, causing the associated cathode-coupled monostable-multivibrator circuit involving the 5965 to fire. The gate pulse from the multivibrator triggers the 2D21 thyratron, causing it to fire and close the two relays in its plate circuit. The plate of the 2D21 is fed by unfiltered ac, so the thyratron will shut off as soon as the multivibrator gating pulse ends; the duration of the gating pulse is about $\frac{1}{3}$ sec. The topmost relay in the thyratron plate circuit discharges a 40-μF capacitor (charged during off-periods by a selenium-rectifier-and-surge-limiting-resistor combination) across the coil of a rotary solenoid. This solenoid indexes a twelve-position six-pole ceramic switch (specially constructed by the author) which steps the six sensing leads from the Digital Recorder to contact with the six staircase-voltage leads of one of the scalers. At the same time, the normally open single-pole double-throw contacts of the other relay in the plate circuit of the 2D21 have caused a 0.01-μF condenser to be charged to about 40 V dc. At the conclusion of the multivibrator gate, the arm of the single-pole double-throw contacts of the relay discharges this capacitor into the print-command lead coming from the Digital Recorder. At the conclusion of the internal printing cycle of the recorder, a "start" pulse from this instrument is capacitively fed to the other grid of the multivibrator, retriggering it and causing the cycle to repeat itself again. After this internal cycle has repeated six times (printing the outputs from four scalers and two blanks), an arm of the plate-circuit relay in the 2D21 plate line, which operates only every sixth time the relay closes, transfers the "start" pulse to all scalers and the timer, which reset and begin another counting period.

This circuit is reasonably conventional. The left-hand grid of the 5965 is crystal-fed to avoid disturbing the circuits in the scaler with back-transmitted pulses. The crystal diode in the other grid circuit clips the multivibrator grid overshoot, thus improving recovery

* Hamner Electronics Company, Service Manual, Model 352 Preamplifier.

time. Switches are provided to intercept the incoming scaler print-command pulse so that total-count information can be made to remain displayed on the scalers. A one-cycle switch can be used to intercept the "start" pulse from the digital recorder if desired. Pushbuttons on the panel can be used to fire the multivibrator or cause the digital recorder to print. A small circuit change involving the addition of a 100,000-Ω resistor to a circuit in the digital recorder was found necessary to induce the recorder to start all four scalers reliably.

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Letters to the Editor *continued from page 164*

A Simple Grating Spectrometer Fore-Prism Drive

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Received 12 August 1962.

A simple mechanical fore-prism drive is described which can be used to make a grating spectrometer a continuous scanning system. In general, a fore-prism must be used to eliminate overlapping orders with a grating monochromator. It is sometimes desirable when using this system to drive the fore-prism with the grating scanning mechanisms in order to make the instrument a continuous scanning spectrometer. This drive eliminates the need for resetting the fore-prism at appropriate spectral intervals as the spectrum is scanned. A simple driving system, which can easily be adapted to most fore-prism grating systems, is described in this note.

A photograph of the monochromators and drive mechanism is shown in Fig. 1 which presents an over-all view of the system. Figure 2 shows the calibration curves for the fore-prism and grating monochromators. The fore-prism is a Perkin-Elmer Model 160 KBr monochromator. The grating monochromator is a Perkin-Elmer Model 210 and it is equipped with a cosecant drive mechanism which produces a linear relationship between wave number and the micrometer screw setting. The linear calibration curve shown in Fig. 2 was obtained with various order lines of a Hg arc using a 300 lines/mm, 64 by 64 mm, Bausch & Lomb replica grating with a first-order blaze at approximately 3000 cm^{-1}. This particular grating can be used conveniently in the first order between approximately 6000 cm^{-1} and 2000 cm^{-1}.

If the grating calibration curve and the fore-prism calibration curve are cross-plotted for the same wave number, then the relationship between the two micrometer drums is obtained. The curve representing the relationship that must be reproduced by a driving mechanism is shown as a solid line in Fig. 3. The drive was designed by first making a linear approximation to the curve in Fig. 3. The linear operation is performed with the gear reduction unit marked C in Fig. 4 (an over-all schematic of the drive system). Fortunately, both the fore-prism and grating monochromator micrometer drums (D and A in Fig. 4) are geared so that standard 48 pitch gears can be used. The gear reduction unit in this particular case was 32:1. In order to obtain the approximate curvature of the line, an off-axis gear (F in Fig. 4) which is the same size as the micrometer drums was used. This off-axis gear is supported by a simple mount which allows the off-axis separation to be continuously varied with a screw adjustment. The drive is then connected to the fore-prism micrometer drum with a long freely moving rack gear (E in Fig. 4). The rack gear is mounted in a tube which is pivoted at the bottom of the fore-prism drum and spring loaded on the off-axis gear. The idler gears (B in Fig. 4) are used to disengage the drive mechanism.

The curvature can then be approximately reproduced by carefully adjusting the eccentricity of the off-axis gear. The "best-fit" that has been obtained is shown in Fig. 3. Obtaining the best-fit is a trial-and-error procedure and takes about a day or so. The fit does deviate, especially at the low-frequency end; however, in general, large fore-prism slit openings are used (about 100 μ), and it is not important to obtain as good a fit as shown in Fig. 3.

Fig. 1. Photograph of the drive mechanism.

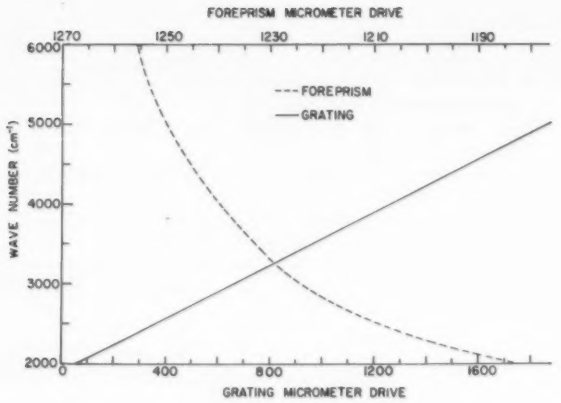

Fig. 2. Calibration curves for the grating and fore-prism monochromators.

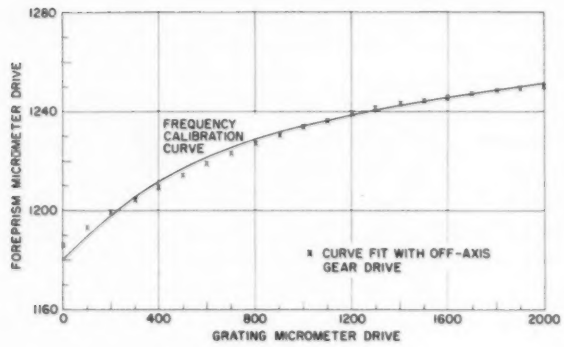

Fig. 3. Curve representing the relationship between the grating and fore-prism micrometer drums.

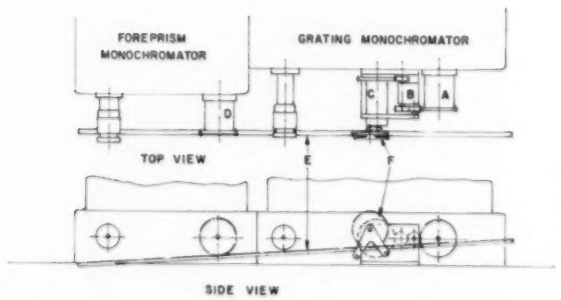

Fig. 4. Detail schematic of the drive mechanism. A—Grating monochromator drum; B—idler gears; C—gear reduction unit; D—fore-prism monochromator drum; E—long rack gear; F—off-axis gear.

The author would like to acknowledge the assistance of E. MacKenzie and A. Kelso who built the mechanical system.

The Abundance of Nitrous Oxide, Methane, and Carbon Monoxide in Ground-Level Air

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This work was supported in part by the Air Force Cambridge Research Laboratories, Office of Aerospace Research, through a contract with The Ohio State University Research Foundation.

The method used to determine the abundance of nitrous oxide (N_2O) in ground-level air, described by Birkeland and Shaw,[1] has been extended so that it is now possible to estimate the abundances of carbon monoxide (CO) and methane (CH_4).

A sample of air at atmospheric pressure is introduced into a previously evacuated 22 m long multiple-traversal cell. Radiation passes through the air sample 32 times to give a total absorption path length of 704 m. Spectra are obtained with a Perkin-Elmer Model 99 double-pass spectrometer containing a LiF prism.

The abundance of these three gases is determined by measuring the integrated absorption of the *P*-branch of the 4.5-μ N_2O band, the *R*-branch of the 4.7-μ CO band, and the *P*-branch of the 3.3-μ CH_4 band. Since these bands are overlapped by bands of water vapor or CO_2 it is necessary to remove these gases from the air sample if accurate measurements are to be made. This was accomplished by passing the air entering the absorption cell over activated alumina which is a selective absorber of H_2O and CO_2. A number of tests were made by placing samples of CH_4, CO, and N_2O in contact with activated alumina and measuring the absorption of the samples for several days. No change in the band absorption was observed, which showed that the activated alumina did not interact with or absorb these gases.

The abundances of the gases are obtained by comparing the absorption of the air samples with the absorption of known amounts of CH_4, CO, and N_2O, pressure broadened to one atmosphere with nitrogen. The abundance of N_2O is found to be 0.28 $\pm$ 0.04 ppm which is in good agreement with the value of 0.27 $\pm$ 0.05 ppm previously reported.[1] Results of about a dozen samples indicate there may be a small (5%) variation in concentration. The abundance of CH_4 is 1.7 $\pm$ 0.3 ppm; no conclusive evidence of any variation has been obtained.

A considerable variation in the abundance of CO has been observed with values ranging from less than 1 ppm to more than 2 ppm. Such variations may be expected since the samples were collected in Columbus, a city with a population of over 400,000 with considerable industrial activity and automobile traffic. The average ground-level CO abundance, 1.3 ppm, is considerably greater than the total atmospheric CO content of between 0.04 and 0.07 atm-cm/airmass obtained from measurements of CO absorption in the infrared solar spectrum,[2] also at Columbus. This increase may again be expected if the lower levels are contaminated by human activity.

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Alteration of the Muscovite Absorption Spectrum by KBr Pellet Preparation

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National Bureau of Standards, Washington 25, D. C.
Received 5 September 1962.

Mary W. Barnes is now at Pennsylvania State University, State College, Pa. Ralph H. Noyce is now at Tarsus Amerikan Colliji, Tarsus, Turkey.

The KBr pellet technique has become a standard sample preparation for obtaining infrared absorption spectra of many solids including minerals. Although quantitative results are claimed for this procedure, some workers have reservations about its use.

Such reservation is corroborated in the case of muscovite mica as is shown in Fig. 1. Here, the absorption spectra are shown for the 10–15-μ wavelength region for an Indian Ruby muscovite. These spectra were obtained with a Beckman IR-4 double-beam, recording spectrophotometer using standard slit schedule, unpolarized light, a NaCl prism, and a wavelength scan speed schedule of 1 μ/min.

Three different sample preparations were used and the resulting absorption spectra are compared. First, a thin film 8-μ thick was cleaved from the original crystal specimen and used directly in the spectrophotometer. The uppermost trace was the result and represents the true spectrum. Then the remainder of the specimen was reduced to flakes in an aqueous medium by a food blender. The water was evaporated away and the residue further reduced in particle size by grinding under alcohol[1,2] which in turn was evaporated away. Some of the resultant powder was placed between the two diamonds of an infrared transmitting diamond cell[3] and the two diamonds were brought together with only enough force to hold the powder in place. The second or middle trace represents the results. Lastly, a KBr pellet was formed in the usual manner with 2.5 mg of the mica powder to 1 g of KBr. The third or lowest trace is the result.

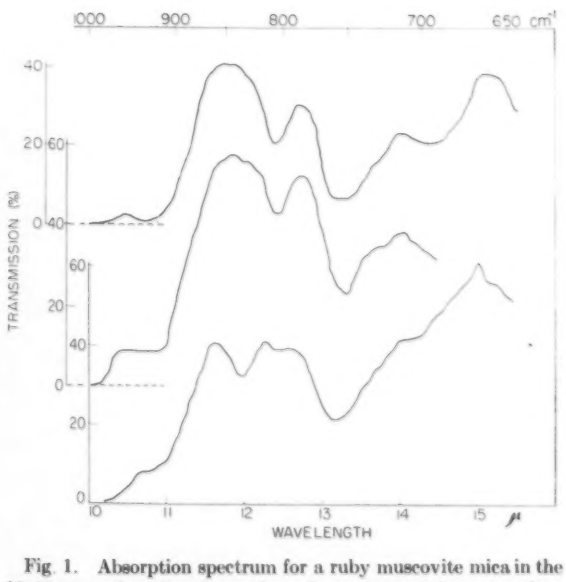

Fig. 1. Absorption spectrum for a ruby muscovite mica in the 10–15-μ wavelength region as dependent upon sample preparation. Top trace is for a cleaved film. Middle trace is for mica powder in a diamond cell. Lowest trace is for mica powder in a KBr pellet.

The third trace for the sample dispersed in KBr is rather distorted from the first trace or true spectrum. That this is a result of the KBr pellet process and not due to the powder preparation is evidenced by the second trace for the powder itself in the diamond cell, which is a reasonable reproduction of the first trace over the range for which the cell is useful. In particular, the 12-μ band is greatly enhanced while the 12.5- and 14.5-μ bands are rather reduced in intensity.

The question arises as to whether such observed spectral deformation is associated with an orientation of the crystallites different from that of cleaved plates, since the pellet preparation might allow a somewhat random orientation. Another sample preparation was made which consisted of a 0.2 mm layer of powder dispersed in paraffin oil supported in a cell with KBr windows which was limited to the ~12 to 13-μ wavelength interval by the paraffin spectrum. An enhanced 12-μ band was not obtained.

It is noted that these very same bands at 12, 12.5, and 14.5 μ have been ascribed to Si—O—(Al) vibrations from an analysis employing KBr preparations.[4]

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Wavelengths of Fe Lines Measured by a New Technique

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Received 17 September 1962.

A large part of the labor involved in the measurement of wavelengths of spectral lines by means of a Fabry-Perot etalon is the derivation of the fractional part of the order of interference. With populous spectra, such as those of iron or thorium, this task is so formidable that a very large proportion of the lines have not yet been measured to interferometric accuracy. The wavelength measurements reported in this paper demonstrate the practicability of a photometric matching technique which gives the excess fraction quickly and directly.[1]

The experimental arrangement used for the measurements is shown schematically in Fig. 1. The Fabry-Perot etalon is enclosed in the sealed, temperature controlled chamber C. Piston P_1 permits the adjustment of the average pressure in the chamber, and piston P_2 causes the instantaneous pressure to oscillate about this average pressure. P_2 is driven by an 8-pole synchronous motor, so that the frequency of oscillation of the pressure is 15 cps. The light at the center of the Haidinger fringe system imaged on the spectrograph slit by lens L_1 is, therefore, modulated in intensity at 15 cps and its harmonics.

At the focus of the field lens L_2 is placed a motor-driven disk with slots S_1 and S_2 cut through as shown in Fig. 2. This disk is driven by a synchronous motor of the same speed as the driver for the oscillating piston. By rotating the frame of the disk

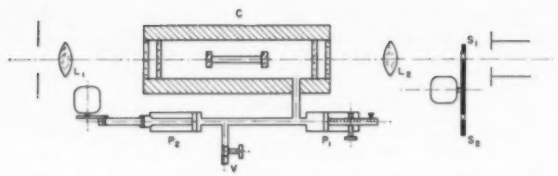

Fig. 1. Schematic of an etalon and associated equipment for rapid measurement of order of interference of many spectral lines.

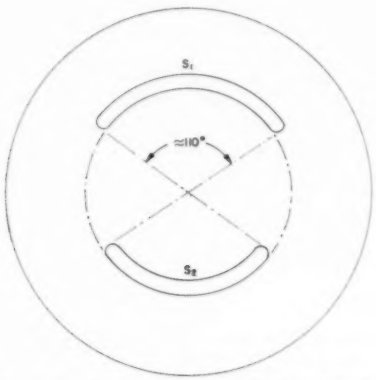

Fig. 2. The motor-driven disk showing the disposition of the two slots.

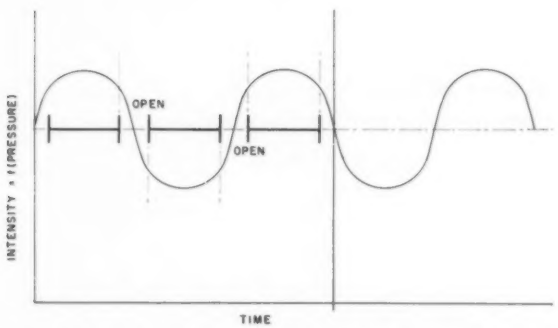

Fig. 3. Variation of intensity with time. The slots S_1 and S_2 pass light during the times of most rapid intensity change.

driven motor the relative phase may be adjusted so that light passes through the system during the times shown in Fig. 3. Slot S_1 passes light to the top half of the central spot, and slot S_2 to the bottom half; if the average optical path is not such that the order of interference is integral, there will be an intensity difference across the common line of the two slots, which can be seen on the photographic image (Fig. 4). If the relative phases of the two motors is not correct, the sensitivity is decreased, but no systematic error is caused.

In the procedure for wavelength determinations, piston P_1 is advanced step by step, and an exposure is taken at each step. The total change in optical path for all the steps is made to exceed one fringe so that at least one exposure will be found for each spectral line which shows a photometric match at the common line of the two slots, or it can be deduced that one would have occurred between some two steps. The steps are made such that a known change in optical path occurs between steps so that, by counting the number of steps, the optical path change from the initial state is determined. At the beginning and the end of the series an exposure of the entire ring system produced by a standard lamp then permits the exact determination of the optical paths at the beginning and the end of the series and hence the optical path corresponding to an integral order number for the unknown line. The wavelength of the line is then easily calculated. The dispersion of the air in the chamber is readily corrected for by the use of the information given by the standard lines. It is apparent, then, that if a large number of lines are to be measured the reduction of the interferometer data is very much simplified.

As an example of the method, some lines in the spectrum from an iron–neon hollow cathode lamp were measured by this technique. The reference standard lines were emitted by an Hg 198 electrodeless discharge lamp, and the etalon optical lengths at the beginning and end of the series of exposures were determined by the classical methods from the standard lines. The setting corresponding to a photometric match was estimated to about one-third of a step interval. The spectrograph used was a two-prism instrument fitted with dense flint prisms, which prevented the measurement of wavelenghts shorter than 3800 Å. The lines reported in Table I are those which had a suitable intensity and were resolved by this spectrograph.

Vacuum wavelengths are given in Table I and, for comparison, the wavelengths reported by Edlén[2] are given in the column λ_{IAU}. The standard line for the region shown was the Hg 198 line at 4046.5717; the corrections to vacuum were taken from Edlen's[3] tables.

Fig. 4. A few steps of a test series, showing the yellow and green lines of Hg 198. The photometric match for the 5792 line is between the third and fourth exposures; for the 5771 line it is near the first.

Table I. Vacuum Wavelengths

λ_{vac}	λ_{IAU}	λ_{vac}	λ_{IAU}
3887.3833	3833	4203.2148	2121
3921.3674	3679	4217.3726	3702
3924.0215	0222	4237.1285	1289
3929.0318	0319	4261.6717	6726
3931.4092	4091	4283.6073	6076
3970.3806	3797	4309.1130	1131
4064.7405	7418	4326.9791	9779
4072.8869	8868	4384.7768	7765
4133.2249	2232	4405.9881	9875
4145.0365	0366	4416.3628	3621
4182.9329	9328	4428.5526	5525
4192.6098	6108		

The standard deviation per pointing between the values given by Edlen and the present results was about 0.0009 Å if the results for 4202 Å and 4216 Å are ignored. The wavelength values for the latter were confirmed on different plates, and may well be due to satellites not resolved by the spectrograph used.

The above figure for the standard deviation is consistent with the fact that the settings for the photometric match could be determined to the equivalent of about 0.0007 Å. As it is unlikely that wavelength values for the iron or thorium lines can be considered significant to better than 0.0005 Å without a thorough investigation of their sensitivity to perturbations, the method of interferometric wavelength determination described appears to be practical for the measurement of such spectra.

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Future Issues

Each issue will specially feature one area of applied optics in addition to the usual contributed papers, shop and technical notes, reports of meetings, Letters to the Editor, book reviews, Meetings Calendar, and special columns. The feature subject of each issue is the responsibility of the named editor.

1963		
March	**Optical Instruments**	W. L. Hyde
April	**Image Evaluation**	F. Dow Smith
May	**Interferometry**	R. A. Woodson
June	**Super Achromats**	—
July	**Spectroscopy**	Mary E. Warga
August	to be announced	
September	**Lens Design and Computers**	D. P. Feder
October	**Bubble Chamber Optics**	S. Rosin
November	**Coblentz Commemoration**	E. K. Plyler
December	**Chemical Optics**	M. Kent Wilson
1964		
January	**Photographic Optics**	George C. Higgins
February	**Atmospheric Optics**	D. Q. Wark
April	**Visibility**	S. Q. Duntley
May	**Microscopy**	J. R. Benford
June	**Fiber Optics**	C. W. Peters
July	**Optics in Japan**	R. A. Oetjen
December	**Solar Optics**	G. Newkirk Jr.
1965		
February	**Plasma Radiation**	L. M. Branscomb

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REFEREES

The following people referee papers submitted to APPLIED OPTICS from time to time, and the Editors wish to acknowledge with gratitude this service:

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OSA Group Flight to Europe

JULY 1963

The revised schedule for the OSA 1963 Group Flight will enable members to attend some of the following July meetings in Europe. (This schedule has had to be revised because, under the new charter agreements, no group flights may take place during the period 24th June/7th July.)

1–Aug 23	Summer School of Theoretical Physics, Grenoble, France
8–13	Ionization Phenomena in Gases Symposium, Orsay, France
10–17	IUPAC Congress, London, England
22–26	Physics of Electronic and Atomic Collisions, London, England
22–27	7th European Congress on Molecular Spectroscopy, Budapest, Hungary

The probable flight schedule is as follows:

7.9.63	Lv New York	SWISSAIR 20:30	7.20.63	Lv Amsterdam*	
7.10.63	Arr Geneva, Switzerland	10:45	7.20.63	Arr Budapest, Hungary*	
7.10.63	Lv Geneva	BEA 12:45	7.28.63	Lv Budapest	MALEV*
7.10.63	Arr London, England	14:10	7.28.63	Arr Zurich, Switzerland*	
7.20.63	Lv London Airport*		7.29.63	Lv Zurich	(Ft #800)SWISSAIR*
7.20.63	Arr Amsterdam, Holland*		7.29.63	Arr New York.	

* Details to be announced

Because there is no same day connection Budapest—Zurich—New York, SWISSAIR will absorb hotel and meal expenses for one day.

Such a round-trip group fare would cost $416 + $4 handling charge, **i.e., $420,** assuming a minimum of 25 participants. This fare includes internal European travel only if the members travel as a group, i.e., the ticket cannot be used for other planes. Forty seats have been tentatively reserved, and we need your deposit ($50 per seat) as soon as possible; the balance of the fare ($370) must be paid by **30th April.**

THIS GROUP FLIGHT WILL BE ON A SWISSAIR REGULARLY SCHEDULED JET AIRCRAFT.

There are three other meetings in Europe in 1963 of particular interest to opticists:

May	2nd Hungarian Optical Conference, Budapest, Hungary
24–26 June	12th Liège Astrophysical Symposium, Cointe-Sclessin, Belgium
late September (tentative)	ICO Symposium on Thin Films, Marseille, France

If sufficient members (minimum of 25 per meeting) are interested, the Assistant Secretary will endeavor to arrange group transportation for these too.

Assistant Secretary, OSA, Room 101,
1155 Sixteenth Street, N.W.
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Tests of Photomultipliers for Astronomical Pulse-Counting Applications

James P. Rodman and Harlan J. Smith

An apparatus is described for testing photomultiplier tubes to be used in an astronomical spectrophotometer. The wide differences in residual nonthermal dark current (after refrigeration) found among photomultiplier tubes with very similar rated characteristics require that each cell intended for faint-light astronomical applications be individually selected. The better CsSb and trialkali tubes which we tested have residual dark currents extrapolated to zero bias respectively in the range 2–6 and 15–30 counts/sec; unfortunately this residual component is usually also somewhat nonstatistical in character. Further general conclusions from our tests are presented, together with specific data for cells including relative-sensitivity scans of photosurfaces.

I. Introduction

The construction at the Yale Observatory in 1961–62 of a multichannel pulse-counting photoelectric spectrophotometer[1,2] made it necessary to obtain photomultiplier cells of maximum sensitivity and minimum refrigerated dark current for operation at extreme low light levels into pulse-counting equipment. While pulse-counting methods have long been employed in connection with nuclear scintillation detectors, in scintillation work one ordinarily utilizes dominant pulses originating from groups of electrons simultaneously released from the cathode by a burst of light from the scintillation crystal, in contrast to which the sparse and singly released cathode electrons dealt with astronomically require a higher order of cell sensitivity, stability, and quiet. Since we found very little in print or available from the manufacturers to guide our selection of cells, we set up a test procedure, the methods and conclusions of which may be of interest despite the provisional nature of some of the results. Limitations of time and funds have thus far made it impossible for us to undertake a complete cell-testing program; rather, after extensive correspondence with manufacturers and users, we chose to study for the present only EMI* cells in view of the company's experience and reputation in the field, variety of astronomically relevant types, and evident interest in attempting to select prime cells for users who really need them. However other manufacturers (e.g., Farnsworth and RCA) have also been interested in producing optimum cells, and the importance of these for photoelectric astronomy is great enough to warrant serious future consideration of a program of testing relevant types from all manufacturers.

Our spectrophotometer requires quiet cells with peak sensitivities around 4000 and 6500 Å, for which the "S" (CsSb) and the S-20 trialkali (SbNaKCs) were respectively recommended as probably the most satisfactory photocathodes currently available from EMI. This note includes at least fragmentary information derived from four "S" and seven S-20 cells; several other cells were rejected immediately on the basis of high noise level.

II. Equipment and Procedure

The testing apparatus diagrammed in Fig. 1 was designed and built by one of us (JPR) to duplicate closely but flexibly the conditions under which we use the photocells. Machined blocks of beaded styrefoam form a complete insulating housing of external dimensions roughly 15 × 30 × 80 cm, enveloping a long copper cylinder containing the cell and test equipment. Methanol, cooled to dry-ice temperature by a simple external refrigerator,[1,2] is pumped through spiral copper tubing soldered to the outside of the test cylinder; this system brings a cell plus its entire working environment from room temperature to −70°C in about an hour, subsequently holding the temperature constant to ±1°. Thermocouple leads, operating a Leeds and

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* EMI Electronics Ltd., Hayes, Middlesex, England.

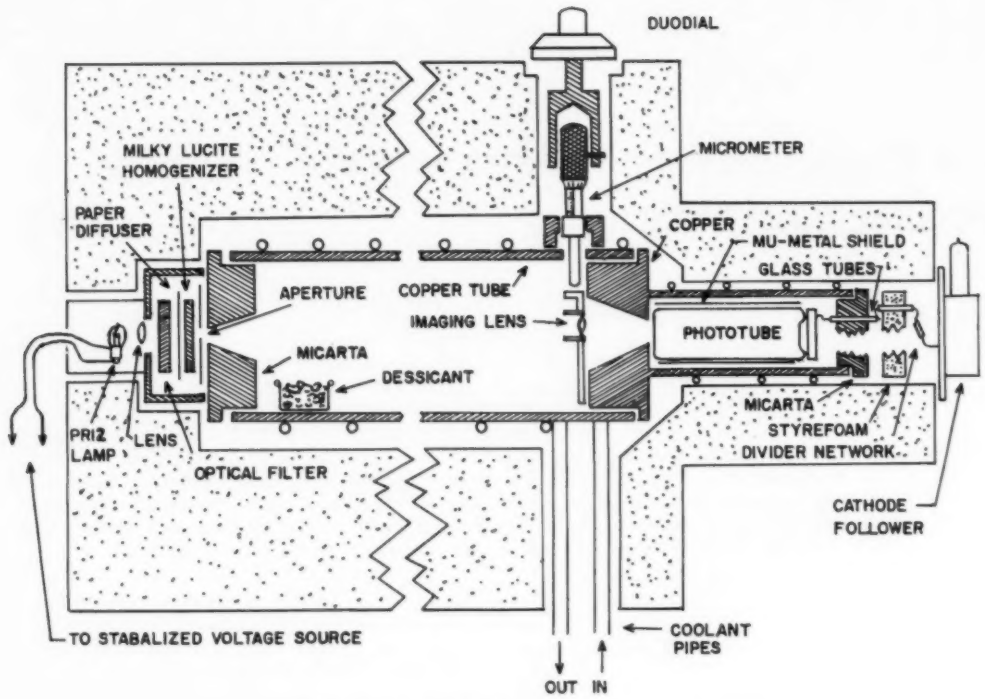

Fig. 1. Diagram of photomultiplier test unit.

Northrup direct-reading temperature potentiometer, are taped to the glass of the cell near the photocathode to insure that the cathode is actually at the indicated temperature. The cell under test slips into a close-fitting mu-metal magnetic shield which in turn is in close contact with the 6-cm diam copper test chamber. Gentle pressure from the dynode lead wires holds the photocathode end of the cell in stable physical and thermal contact with a perforated copper block at the end of the cell chamber. All parts of the chamber are grounded, along with the photocathode (easily arranged in pulse-counting work), an important insurance against troubles and dangers from high fields. The cell plugs into a standard Teflon socket from which the dynode leads run through glass tubes in a micarta chamber-sealing plate, then through further glass tubes in a block of insulating styrefoam, and finally to the resistors of the voltage-dividing chain. A cathode follower with 10^{-5} sec time-constant, built onto the external plate of the base assembly, provides impedance match to an RG 59 U coaxial cable feeding a Hamner N 371 linear amplifier and discriminator which in turn triggers a Hamner N 276 scaler of 10^6 cps resolution (the cathode follower setting the resolution limit of the system). A Hamner N 803 crystal-controlled clock permits choice of integration times ranging from 1 to 5000 sec; at the end of the preset time the integrated scaler count is printed out by a Hewlett-Packard 560 A digital recorder and the cycle is automatically restarted. High-voltage to the cell comes from a Hamner N4035 regulated high-voltage supply monitored by a Hycon 615 AR digital voltmeter; all of the electronics are supplied by a Sorensen 5000S 0.1% line-voltage stabilizer.

Proper illumination for light-tests is generated in a 10-cm diam copper tube shown at the left in Fig. 1; this tube is also cooled in order to help the photocathode reach and hold uniformly low temperatures. A PR-12 bulb was chosen as light source because of its stability and minimal bulb-darkening propensities; it is supplied from the stabilized line voltage through a powerstat and precision voltmeter so that intensities can be closely repeated over long intervals. The optical train consists of a collimator lens, a spectral filter, a paper diffuser, and a milky lucite homogenizer, the diffuse light from which illuminates a precisely defined sharp-edged aperture in a sheet of stainless steel. This aperture, which governs the size of the final light test spot, is imaged on the photocathode by a lens located in a precision fixture mounted at the junction of the two chambers. A micrometer external to the box works through an extended shaft to move the lens, and hence the focused spot on the photocathode, up and down by accurately known amounts. While this arrangement

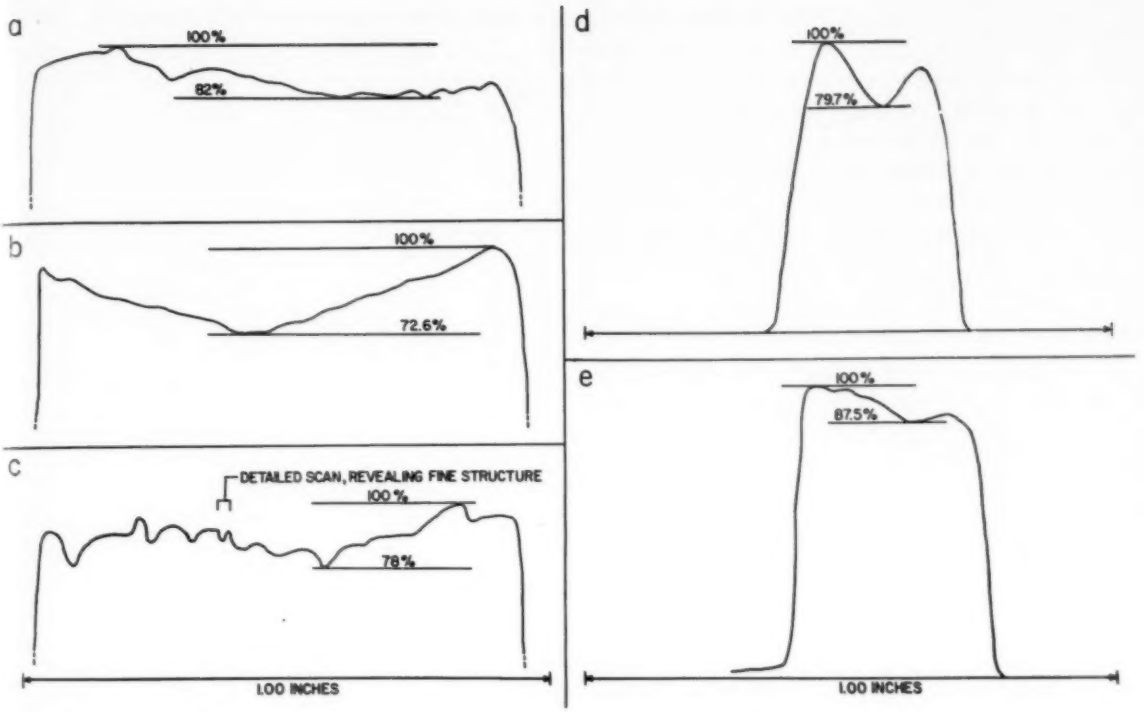

Fig. 2. Typical scans of photocathodes, made with 0.25 mm light spot. Scans a, b, c are of EMI 9558 A trialkali S-20, Nos. 5844, 5833, and 5938; scans d and e of EMI 9502S CsSb No. 5598 and 6256SA Nos. 11519.

permits only linear diametric scans of photocathodes, the cell base assembly is free to rotate so that scans can be made across the cathode at any desired angle. Red cells were tested through a 15 Å Baird interference filter centered at Hα (6563 Å), blue cells through Corning 5840 and 5543 5-mm glass filters generating a 500 Å passband centered at 3800 Å and having a negligible red leak.

The apparatus is thus well adapted to determining total values, stabilities, and statistical character of both dark counts and light counts over a wide range of temperature, applied voltage, amplifier gain, or discriminator setting; also to measuring the sensitivity of very small areas of the cathode as a function of position.

III. Results of Tests

A. Sensitivity

With each cell, EMI supplies a rating giving on an arbitrary scale the room-temperature cathode luminous sensitivity at several wavelengths. As is not surprising, we find that refrigerated cells exposed to our standard light have closely the same ratio of pulse-count sensitivities as do the values given by EMI for the appropriate wavelength region. A factor of about 8 in quantum efficiency separates the weakest (C-grade) cell we have tested from the best (A-grade) cell highly selected for sensitivity in a specific part of the spectrum.

We have as yet no satisfactory way of checking on the absolute quantum efficiencies quoted by the manufacturer; however, the following argument indicates that when in use the cells give counts which are entirely consistent with the manufacturer's rated quantum efficiencies. A star of $m_v = 5$, seen vertically through an atmosphere with visual extinction coefficient $\alpha_v = 0.2$ yields $\backsim 2.0 \times 10^{-12}$ lumens cm^{-2} (ref. 3, p. 24). Since at 5550 Å, 1 lumen $= 1.47 \times 10^{4}$ ergs cm^{-2} sec^{-1} (ref. 3, p. 23), then (from $E = h\nu$) to the surface of the earth the star gives a minimum flux of $\backsim 8.2 \times 10^{3}$ photons cm^{-2} sec^{-1} over the entire 1068 Å equivalent width (ref. 3, p. 103) of the visual passband. Our equipment utilizes only a 15 Å passband at Hα, where the energy flux per unit bandwidth should be (for early K-type stars) close to that around 5550 Å; however the Hα region has about 28% more photons per unit of energy flux. Accordingly the incident flux from a 5th magnitude early-K star should be

$$\backsim 1.5 \times 10^{2} \text{ H}\alpha \text{ photons cm}^{-2} \text{ sec}^{-1}.$$

We observe this flux with a telescope-spectrometer having a useful collecting area of 1.8×10^{3} cm^2, but only 15% efficiency [5 aluminized mirrors (30%), 1 grating (65%), one wide slit (95%), and 4 air–glass surfaces (80%)], for an effective collecting area of 2.7×10^{2} cm^2. With a good 9558 Å photomultiplier, the

system gives 1800 Hα light counts/sec from an early K star of $m_v = 5$, or

$$\sim 6.7 \text{ H}\alpha \text{ photon counts cm}^{-2} \text{ sec}^{-1}.$$

The quantum efficiency thus appears to be about 4.5%, in agreement with the 4–8% which might be expected from the rated curves for S-20 surfaces. However, a principal uncertainty in this result is the conversion from lumens to photons; also it is entirely possible that losses in our optics are significantly different from those assumed in this calculation.

B. Uniformity of Photocathode

All the cathodes tested proved to be significantly nonuniform. Figure 2 presents typical linear scans, made with a spot of 0.025-cm diam, moved by 0.063-cm increments. We found extreme differences of sensitivity over a cathode amounting to about 25%. Nonuniformity extends to very small areas of the photosurface; moving the 0.025-cm spot by 0.0063-cm increments revealed fluctuations of several percent (see Fig. 2, curve C).

C. Stability

About a quarter of the tubes available for testing possessed what we presume to be internal discharge or leakage generating hundreds or thousands of counts per second. At least in the case of S-20 surfaces, this would normally be masked by room temperature dark currents and thus would not show up in the manufacturer's tests. Such cells are of course totally unfit for astronomical pulse-counting applications. The discharge does change somewhat with aging under high voltage, disappearing entirely in one of our cells over several weeks of use, but getting worse in others. In another case the discharge was highly sensitive to mechanical shock; lightly tapping the cell caused gross metastable changes in the noise.

D. Thermal Dark Current

The true cathode thermal-emission component of dark current is given for ideal metallic surfaces by Richardson's law (see ref. 4, p. 145):

$$I = a\, T^2 \exp(ew/kT)$$

in which for our purposes only the current (I) and the temperature (T) are variables. Our pulse-count data fit this relation well for a single work function w in typical cooling runs on trialkali cells (Fig. 3) over the range +20 to about 0°C. Below −20° the extrapolated Richardson thermal dark current becomes lost in the residual noise of the cells. While several different work functions from the cathode and surrounding areas are presumably involved in the total curve, Fig. 3 suggests that if thermal emission were the only factor present, cell noise would become truly negligible for most purposes (<1 count/min) by the easily attainable temperature of −60°C.

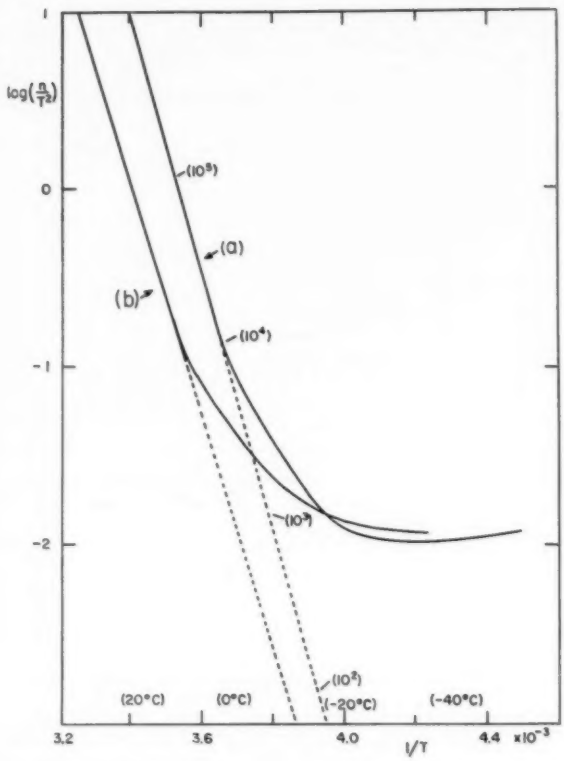

Fig. 3. Richardson's-law curves showing 50-sec integrated dark counts as a function of temperature for two EMI trialkali cells. Solid curves: observed data for (a) 9558A No. 5844, (b) 9558C No. 5462. Dotted lines indicate extrapolated thermal emission based on primary work function; parenthetical numbers refer to the thermally originating pulses assumed to be associated with that work function for each temperature of No. 5844.

A small computer program was applied to much of the test data. Typically, the observed standard deviation (σ_0) of the residuals from the mean of 20 integrated counts taken under identical conditions was compared with the standard deviation to be expected (σ_e) from the counted numbers. For light counts, and for dark counts when the thermal dark current predominated strongly, the ratio σ_0/σ_e did not depart significantly from unity—that is, the thermally and light-emitted electrons from the cathode had the expected random distribution.

E. Nonthermal Dark Current

Since the residual dark current below −20°C is essentially independent of temperature (it even tends to increase slightly in most of our cells with cooling from −30° to −70°C), we refer to it as the nonthermal

Table I. Sample Run of Residual Nonthermal Nonstatistical Dark Current (EMI 9558A, #5833)

50-sec counts n	$n - \bar{n}$	50-sec counts n	$n - \bar{n}$
1455	−073	1779	+250
1295	−233	1438	−090
1364	−164	1482	−046
1658	+129	1402	−126
1589	+060	1621	+092
1433	−095	1577	+048
1529	+001	1792	+263
1487	−041	1583	+054
1464	−064	1324	−204
1549	+020	$\bar{n}$: 1528	σ_0: +138
1747	+218	$\sqrt{\bar{n}} = \sigma_e$: 39	$\sigma_0/\sigma_e = 3.5$

component of dark current. In our tests this component amounted to several counts per second for good CsSb cells and about 15–30 counts/sec for the best trialkali cells in normal behavior.

The nonthermal dark current is usually somewhat burstlike and nonstatistical in character; σ_0/σ_e differs for each cell, ranging from 1 up to 3 for those cells which we found otherwise acceptable. The erratic character of this noise renders it the equivalent of a statistical dark-current $(\sigma_0/\sigma_e)^2$ times greater than that actually observed, in terms of the statistical limit which the dark current places on observations of faint light sources. Table I reproduces a typical sample of the nonthermal dark-current counts made with our most sensitive cell, illustrating the character of the scatter. Table II summarizes the observed count characteristics of all the cells tested.

We believe it unlikely that the nonthermal dark current arises from external leakage or poor pin contact, since it is absent when a cell is unplugged and has a value characteristic of a given cell which is generally repeatable each time the cell is tested even after intervals of several months. The noise can be shown to be associated with the cathode, since it disappears entirely when the cathode is given the same potential as the first dynode, with 2 V reverse bias to hold back any electrons thermally emitted from the cathode.

The nonthermal component is not very sensitive to applied voltage. In one test made with a fixed discriminator setting, variation of total dynode voltage from 1300 to 2000 V increased the nonthermal dark counts and the σ_0/σ_e ratio each by about 25%.

Over a range of integration times from 1 to 200 sec, σ_0/σ_e is constant for each cell. This behavior is consistent with the hypothesis that the nonthermal counts are not fully independent, but rather that on the average there are $\sim(\sigma_0/\sigma_e)$ counts triggered by each of the random events responsible for the nonthermal counts. The extra counts may be related to the ionization "after-pulses" referred to by Lallemand (ref. 4, p. 153).

Finally, it may be worth noting that one otherwise excellent 9558 Å vacillated between two modes of behavior. At the start of each run, on first having voltage applied, the cell would show very high sensitivity, but also high nonthermal dark current with $\sigma_0/\sigma_e \sim 1.5$. After two hours, a few minutes of violent noise would inevitably ensue, followed by a new stable operating mode having about 20% of the previous sensitivity and dark count but now a more nearly statistical behavior of the dark count ($\sigma_0/\sigma_e \sim 1.1$). Since this cell was also inordinately sensitive to mechanical shock, it is plausible[5] that something within the cell was able to short a pair of dynodes; when incipient the short contributed to the noise of the cell either directly, or indirectly through the amplification of the stage.

F. Miscellaneous Effects

New cells usually require about a day of aging under high voltage to reach stable operating conditions with normal low dark count. After exposure to bright light, even without applied voltage, a seasoned tube may require up to several hours to recover stability.

Table II. Refrigerated Dark-Count Data for EMI Photomultipliers[a]

Cell		Cathode		Mean No. dark counts/	
Type	Serial	Diam	Type	sec	σ_0/σ_e
9558C	5312	5 cm	S-20	18	1.8
9558C	5415	5 cm	S-20	33	2.6
9558C	5462	5 cm	S-20	15	2.7
9558C	5496	5 cm	S-20	22	3.0
9558A	5833	5 cm	S-20	31	2.8
9558A	5844	5 cm	S-20	14	1.5 (before discharge)
9558A	5844	5 cm	S-20	4	1.1 (after discharge)
9502S	5598	1 cm	CsSb (S)	6	1.0
6256SA	11519	1 cm	CsSb (S)	2	1.1
6256SA	11731	1 cm	CsSb (S)	5	1.1
6256SA	11715	1 cm	CsSb (S)	14	1.1

[a] Most of these results are means of several test runs; all were made at $T < -20°C$, usually $-65°C$, and with 2000 V applied to cells.

IV. Conclusions

Commercially available photomultipliers exist with S-20 and CsSb surfaces having respectively quantum efficiencies probably approaching their rated 5% in the deep red and 20% in the violet, which after refrigeration have residual nonthermal dark counts of about 20 and 2 per second respectively. However, such cells are found only as a result of the manufacturer's initial general selection for high sensitivity without obvious gross discharge, coupled with the user's further selection for those cells with sufficiently low refrigerated dark noise. Good quantum efficiency gives these cells a high information-gathering rate appropriate for most astronomical applications, but the residual dark count and its somewhat nonstatistical character discourages use of the trialkali cells on the fainter astronomical objects which yield only a few photon counts per second (see the discussion of signal-to-noise ratio by Baum[6]). Artificial increase of the scalar dead-time when one is working at low light levels should markedly improve dark-counts and their statistics.

The manufacturer's relative-sensitivity ratings are a useful guide to the cells' working pulse-count quantum efficiency, but the room-temperature dc dark-current ratings supplied with the cells give little or no useful information on the residual nonthermal dark count to be expected. Attempts made in manufacture to reduce dark current by special surface treatment may well prove irrelevant to astronomical practice for properly cooled cells; indeed should such treatment reduce photocathode sensitivity it might even be deleterious to over-all signal-to-noise ratio.

Astronomers may expect to profit from having available S-20, or any other astronomically useful, surfaces deposited as small cathodes—say 10 mm as with the EMI 9502S—since this should normally reduce dark counts by a very important factor while leaving the astronomically useful area of the cathodes unimpaired.*

We wish to express sincere thanks particularly to Jack Sharpe of EMI, England, and to Fred Belasco of EMI, U.S., for their helpful suggestions, cooperation and patience during this work.

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* Farnsworth has been developing such a cell and has kindly offered a sample for testing; modification of our test chamber will permit this.

George Vanasse and E. V. Loewenstein, *Geophysics Research Directorate,* and John Strong, *Johns Hopkins University,* work it out.

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Concave Gratings for Astronomical Spectrographs and Spectrometers

William Liller

Concave gratings possess a number of characteristics which should make them of interest to earth-bound stellar spectroscopists. Evaluation of a number of specific spectrograph and spectrometer designs indicates that concave grating instruments can be extremely efficient, and therefore are particularly suitable for nebular spectrographs and broad-band spectrophotometry.

Introduction

In recent years much effort has gone into the development of astronomical detectors with high quantum efficiencies. The so-called trialkali photocathodes (S-20 response) now respond to 20% of the incident photons at the wavelength of peak sensitivity ($\sim\lambda$4200 Å).[1] Hiltner[2] and others have described image intensifiers with these cathodes and with multiplier stages yielding total gains of the order of 10^4. In most instances these modern detectors are used in conjunction with fast optical systems such as solid Schmidt cameras, Baker super-Schmidt cameras, and exotic lens systems. It is therefore rather surprising to find that many visible light astronomical spectrographs and spectrometers, particularly those of high resolution, and even many low resolution instruments, transmit less than a third of the light passing through the entrance slit. A typical stellar spectrograph[3] used on a Cassegrain telescope (two or three reflections) is a rather bulky affair which has an image rotator (one transmission), an inverted Cassegrain collimator (two reflections), a blazed grating (70% efficient), a Schmidt correcting lens (two transmissions), a camera mirror (one reflection), and a field flattening lens (one transmission). Under good conditions, each reflecting surface and each transmitting component will reflect or transmit about 90% of the light. Thus the total efficiency of the spectrograph just described will be $(0.90)^7 \times 0.70 \times 100 = 33\%$. If the surfaces of the optical components drop to 80% efficiency, then the entire spectrograph will pass less than 15% of the incoming radiation. The substitution of a train of prisms for the grating would lower the total transmission even further. These facts are most disheartening to an astronomer facing a one hundred hour exposure stretched over several midwinter nights.

Satellite astronomy has introduced the techniques of ultraviolet spectroscopy to astronomers. One of the more intriguing devices used in this field is the concave grating which immediately reduces (or eliminates entirely) additional reflections or transmissions in a spectrograph. Not only do the smaller number of reflections permit more compact instruments, but also they make possible highly efficient systems with good resolution. The immensely successful use of concave gratings in rockets by Tousey,[4] by Rense,[5] and by others has produced superb solar spectrograms at wavelengths below λ3000.

The visible light stellar astronomer and the ultraviolet physicist have at least one basic and rather difficult problem in common: to provide enough photons at the detector. The astronomer has few photons to start with; the ultraviolet physicist must work with inefficient reflecting surfaces and low transmission optics. Both must design efficient analyzing systems.

The concave grating was first introduced by Rowland,[6] and although there have been many subsequent articles on its use, Rowland's fundamental ideas remain basic to nearly all modern applications. Rowland noted that the grooves of a concave grating should be ruled in such a way that they appear parallel and equally spaced when viewed from an infinite distance. The *Rowland circle*, as it is now known, is a circle with a radius exactly half the radius of curvature of the grating, with its center on a line perpendicular to the grating center, and with its plane perpendicular to the rulings of the grating. Rowland showed that if the

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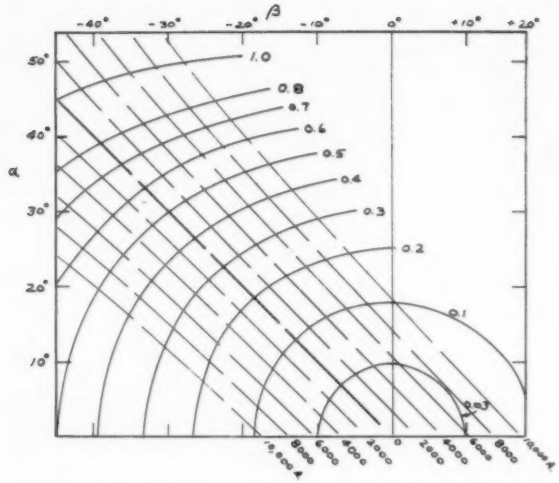

Fig. 1. The amount of astigmatism (solid lines) and the wavelengths (dashed lines) for a 300 grooves/mm grating as a function of the angles of incidence (α) and of diffraction (β). The unit of astigmatism is the length of the grating ruling.

entrance slit were located anywhere on the circle and perpendicular to it, then the final spectrum would also lie on the circle. Furthermore, the equation describing the performance of the plane grating applies, namely

$$\pm n\lambda = d(\sin\alpha + \sin\beta), \tag{1}$$

where n is the order, d the ruling spacing, and α and β are the angles of incidence and diffraction, respectively. If the incident and diffracted rays are on opposite sides of the grating normal, then $\sin\alpha$ and $\sin\beta$ will be of different sign. If the incident and diffracted rays are on opposite sides of the zero order reflection, n is negative. From Eq. (1) there follow the expressions for angular dispersion,

$$d\lambda/d\beta = d\cdot\cos\beta/n, \tag{2}$$

and for linear dispersion,

$$d\lambda/dx = d\cdot\cos\beta/nR. \tag{3}$$

Here R is the radius of the Rowland circle. It is not difficult to show that the distances from the grating center to the entrance slit and to the final focus are very nearly $R\cdot\cos\alpha$ and $R\cdot\cos\beta$, respectively. The derivations of these and other relationships are given in such standard texts on spectroscopy as those by Sawyer,[7] by Harrison, Lord, and Loofbourow,[8] and in an exhaustive paper by Beutler.[9]

The most serious disadvantage of a simple concave grating spectrograph is the astigmatism introduced. Specifically this causes a point of light at the entrance slit to be drawn out at the focus into a line perpendicular to the Rowland circle. As was first shown by Runge and Mannkopf,[10] the length of this line

$$z = (\sin^2\beta + \sin\alpha\,\tan\alpha\,\cos\beta)\,l, \tag{4}$$

where l is the length of the grating rulings. Figure 1 shows curves of the quantity in parentheses (solid lines) as functions of α and β. Crossing through this graph are dashed curves indicating values of wavelengths from 0 to 10,000 Å for a 300 lines per millimeter grating. It is at once clear that in visible light spectrographs the length of the lines cannot be less than seven-thousandths the length of the grating rulings. For best performance one would generally choose to work with approximately equal (algebraically) values of α and β.

Several schemes have been devised to reduce or eliminate astigmatism. Green and Loring[11] use a sphero-cylindrical lens in front of the plate, while Smyth[12] introduces a spherical mirror before the entrance slit. A variation of Smyth's method has been successfully used by Rense and Violett[13] in a rocket spectrograph.

For a concave grating *spectrometer*, at the focus of which is an exit slit and a photomultiplier, moderate astigmatism is of little consequence, as long as all the light strikes the photocathode and avoids areas of low sensitivity. Usually it is desirable to image the objective of the telescope on the photosensitive surface of the detector. As will be seen in a later section, this condition can be fulfilled to a good approximation. A short astigmatic image would actually be a blessing to a stellar astronomer who, in using a *spectrograph*, usually desires a somewhat widened spectrum of his stellar point of light. For example, a 50 mm square grating with 300 lines/mm produces a spectrum which is about 350 μ wide* at λ4000. Later we will consider the several means available for reducing this astigmatism.

A second disadvantage of concave grating spectrographs is the curved focal surface. It should be noted, however, that photographic emulsions are available on glass plates having a thickness of 0.010 in. (0.25 mm), and to bend such plates to a radius of curvature of half meter is not difficult. For less exacting use commercially available film can, of course, be used.

Before we move to the next section, it should be noted that today concave replica gratings are readily available in a wide variety at reasonable costs. For an example, Bausch & Lomb lists a half meter radius of curvature grating with a ruled area of 28 × 40 mm and with 600 grooves/mm blazed at λ4267 Å. This grating is tripartite; i.e., the blaze angle of the diffracting grooves was changed twice during the ruling so that the curvature of the grating does not alter the

* It should be noted that both the words *width* and *height* are used to denote the dimension of a spectrum measured perpendicular to the dispersion. Here we will use the word width, or variations thereof.

wavelength of the blaze markedly over the grating surface. There usually is some loss of resolution, however, in tripartite gratings. As yet, only spherical concave gratings are available. Except for the final section of this article, in which the potentialities of ellipsoidal and toroidal gratings are examined, all discussions will be limited to the use of spherical gratings.

In the following section we discuss different possible concave grating spectrograph designs suitable for astronomical work in the visible spectrum. The third section contains a description of mountings for spectrometers intended for similar use. In the final section we consider the advantages of nonspherical concave gratings.

Spectrographs

Many excellent articles on concave grating spectrographs have appeared elsewhere[14] or will appear soon.[15] The astronomer wishing to investigate more thoroughly the properties of the various mounting arrangements described in the following paragraphs is advised to refer to these.

Except for the Wadsworth mounting, all concave grating spectrographs in general use today are based on the principles first described by Rowland.[6] Individual mountings, which will be discussed briefly below, are distinguished by their different means of adjustment to allow different parts of the spectrum to be photographed or to permit one to work near the grating normal where the dispersion is linear. Since earth-bound astronomers frequently work over hardly more than a single octave of spectral frequencies, and usually need not make such adjustments, only brief mention will be made of each mounting. More complete descriptions of their performance may be found in the original articles referred to or in the standard textbooks on spectroscopy cited above.

Interestingly, the earliest mounting used, that of *Rowland*,[16] is relatively complicated compared to the currently more popular mountings. Both grating and plate holder move together along perpendicular axes which lie in the plane of the Rowland circle. These axes have their origin at the entrance slit; therefore, the incoming light always is directed along the grating axis. The main virtue of this mounting is that it keeps the plateholder near the grating normal; its major disadvantage is that it requires precise motion of components. A few years later, Abney[17] described a simpler mounting in which grating and plateholder are fixed at the ends of a diameter of the Rowland circle and whereby the entrance slit swings at the end of a radius of the Rowland circle. However, the changing direction of the incoming beam presents design complications for astronomical use. Probably the most frequently used mounting today and in many respects the simplest is the *Paschen* or the *Paschen-Runge* mounting.[18] Here the entrance slit and grating remain fixed; different spectral regions are recorded simply by moving the position of the photographic plate. In the *radius* or *Beutler*[7] mounting the entrance slit and the plateholder remain fixed while the grating slides along the Rowland circle at the end of a radius. More complicated but more compact is the *Eagle*[19] mounting in which the diffracted ray nearly doubles back along the paths of the incident ray of the grating. A small right angled mirror or prism is occasionally used in this mounting, and the entrance slit is the component placed at the "Newtonian focus." To shift wavelength range requires altering the distance of the grating from the plateholder and rotating the grating simultaneously. Because the angle of diffraction is positive in the Eagle mounting, astigmatism can be reduced to a minimum.

In all of these mountings the concave grating replaces both the collimator and the focusing mirror of the plane grating spectrograph. In doing so, however, astigmatism is introduced which, although it does not spoil resolution, reduces the brightness of the final spectrum. At the cost of a single additional reflection, the *Wadsworth*[20] mounting eliminates or greatly reduces the astigmatism. Here a spherical mirror (or lens) serves as a collimator; astigmatism and coma both become zero at the grating normal. To change spectral region, therefore, both plateholder and grating should be rotated around the center of the grating so that the desired spectrum always appears near the grating normal. A consequence of the use of the collimating mirror is, of course, that the distance from the grating to the final focus is reduced by about a factor of two. Thus, the dispersion of the final spectrum in a Wadsworth mounting is similarly decreased. Focal ratios below about six are not too satisfactory because of increasing amounts of spherical aberration, and according to Beutler,[9] little is gained by going to nonspherical mirrors. However, J. G. Baker has used a mounting with the grating serving as the collimator and with a fast Schmidt camera following it. The optical axes of the grating and the camera coincide in this arrangement.

For visible light astronomical spectrography, it seems that the Paschen or the Wadsworth mounting is most suitable. If the "prewidened" spectra produced by the Paschen design are not objectionable, then high resolution, high dispersion spectra can be simply and inexpensively provided. Operating in the first order, a half meter radius of curvature grating having 600 lines/mm produces a dispersion at the grating normal of 33.3 Å/mm in the Paschen mounting. If the entrance slit is located so that the Hδ line of the Balmer series (λ = 4101 Å) falls at the grating normal, then the width of the spectrum is 0.063 times the length of the grating rulings. An $f/15$ telescope requires a

grating approximately 35 mm square which, therefore, would yield at Hδ a spectrum 2.2 mm wide and would have a theoretical resolution of about 20,000 or 0.2 Å. At 33.3 Å/mm, the size of the emulsion grain would limit the resolution at four- or five-tenths of an angstrom. A grating of larger dimensions would be needed if a telescope of smaller focal ratio were used; the resulting spectrum would be wider and there would be no increase in resolution, all else remaining equal. A larger number of lines per millimeter would increase the dispersion and hence the resolution, but since the angle of incidence would also increase for a given wavelength, the width of the spectrum would increase correspondingly (see Fig. 1). A convenient rule of thumb is that the width of the spectrum increases as the square of the number of grating rulings per millimeter. On the other hand it should be noted that the width of the spectrum is independent of the radius of curvature of the grating.

If high resolution with not unreasonably wide spectra is desired, then clearly the best Paschen mounting spectrograph would contain a medium sized grating with a large radius of curvature but with as few lines per millimeter as possible. If practicable, both incident and diffracted rays should be on the same side of the grating normal. For example, an $f/67$ Coudé focus might employ a Paschen spectrograph having a 100 line/mm grating with a radius of curvature of 10 meters. At normal incidence the first order dispersion of such an instrument would be 10 Å/mm, the resolving power 15,000 ($\Delta\lambda = 0.3$ Å at Hδ), and the width of the spectrum 0.25 mm. The diameter of the grating would be 15 cm, a size not difficult to obtain today. Working in the nth order changes all these quantities by a factor of n except the width of the spectrum which increases approximately as n^2. Therefore, the usual choice would be to work in the first order.

Because of the saving of reflections, the best use for a Paschen mounting in earth-bound astronomical spectrography is for faint source, low dispersion work. An interesting instrument for nebular and stellar spectrography might be designed around an 11.5 cm radius of curvature grating having 150 rulings/mm. A normal incidence Paschen mounting at the focus of an $f/5$ reflector would produce a first order spectrum with a dispersion of 580 Å/mm and a width of 0.09 mm at Hδ. The grating would be only 24 mm square. Clearly, the resolution would be limited by photographic grain and typically would be about 10 Å. At the focus of an $f/5$, 60-in. (153-cm) reflector, the diameter of a star image might be 0.05 mm on a night of good "seeing"; a slit just wide enough to admit an entire image of this size would result in a spectrum having a resolution of some 30 Å. Such an instrument would likely be unsurpassed in efficiency; possibly a spectrograph employing a low density prism with convex surfaces and with antireflection coatings might be faster.

The Wadsworth mounting is to be preferred if a stigmatic image is desired; not only will an unwidened spectrum be produced, but also, of course, the variation in spectrum along a slit may be studied. Since astigmatism is eliminated, considerable advantage will result, therefore, by going to large gratings with many lines per millimeter.

In summary, Paschen mountings can be used for astronomical spectrography with outstanding success under proper conditions. There is no more efficient spectrograph if the spectra produced are widened no more than necessary. At the cost of a single additional reflection, stigmatic spectra can be produced, thereby making it possible to use gratings that will give a higher dispersion and resolving power than is possible with the Paschen mounting.

Spectrometers

Many of the advantages and disadvantages discussed in the preceding section apply also to spectrometers. In considering spectrometer designs, however, thought must be given to the ease of achieving the wavelength scan. All of the mountings described above are rather complex as far as changing the wavelength at the exit slit is concerned. Scanning is achieved by moving two components (Rowland, Wadsworth), by both translating and rotating one component (Eagle), or by moving the detector (Paschen, Rowland, Wadsworth). Two mountings require the direction of the incoming beam to be altered (Abney, radius). Further descriptions of these and of other concave grating spectrometers have been given in an excellent article by Namioka.[21]

Because of these disadvantages two relatively recent mountings have been proposed, both of which we will describe in moderate detail. Both only approximate Rowland's criteria for in-focus spectra, and therefore neither can be used for very high-resolution spectroscopy over a wide range of wavelength. The first and more popular design is the *Seya-Namioka*[22, 23] mounting wherein the angle between incident and diffracted ray is held constant at 70°15′. Wavelength scan is achieved by rotating the grating about its vertical axis. Under these conditions, as Seya first suggested and Namioka later investigated, aberrations are reduced to a minimum over a wide range of wavelengths. Best focus results when the distance from each slit to the grating is $0.818\,R$.

The second design is the *Johnson-Onaka*[24, 25] mounting in which the grating rotates about some exterior point whose precise position has been calculated by these investigators. This mounting has not achieved the popularity of the Seya-Namioka mounting largely because it is limited to moderately small wavelength ranges. The primary disadvantage of the Seya-Namioka mounting is the large amount of astigmatism which

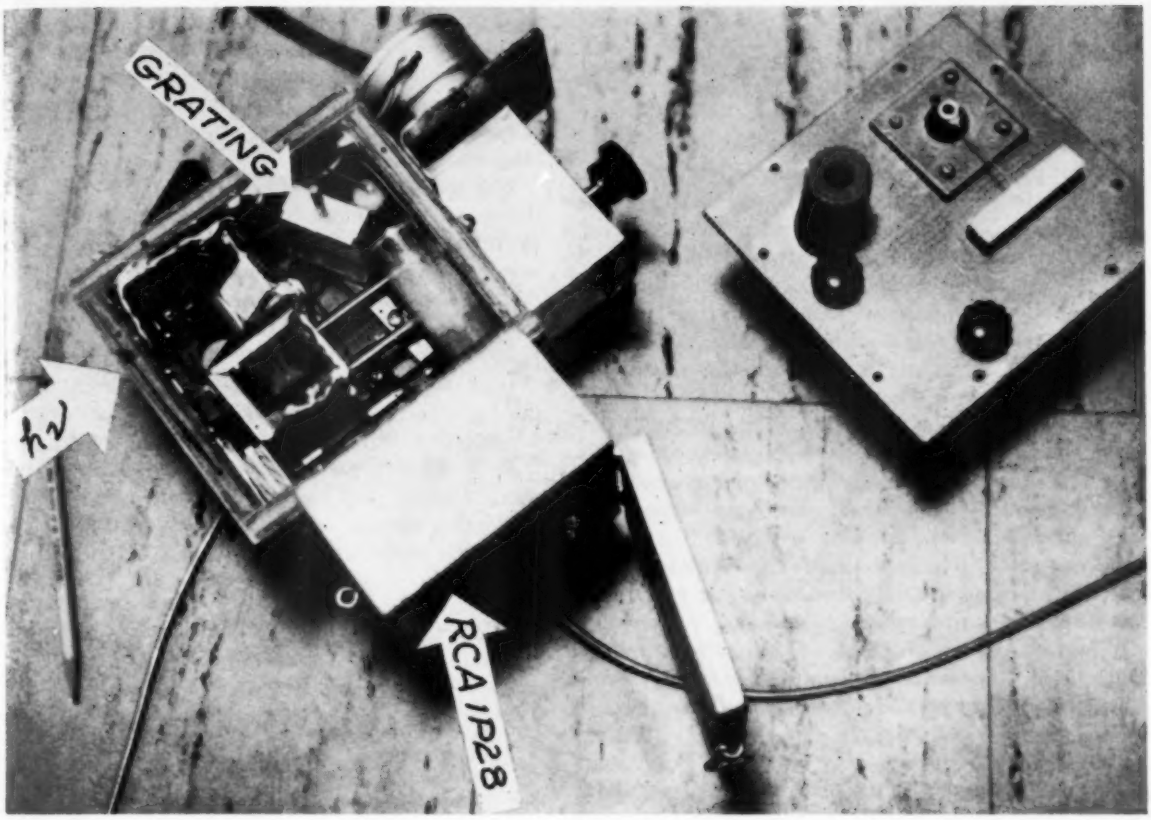

Fig. 2. A Seya-Namioka spectrometer designed and constructed by the author for use at visible and near-ultraviolet wavelengths. The grating with 600 lines/mm has a radius of curvature of 11.5 cm; the detector is an RCA 1P28 photomultiplier. It is normally used at the $f/5$ focus of the 61-in. (155-cm) reflector of Harvard College Observatory.

produces a spectrum whose width for a 600 line/mm grating is approximately two-thirds the length of the grating rulings. Furthermore, according to Namioka,[21] loss of resolution occurs unless the grating width is carefully chosen.

For moderately low-resolution scanners using small gratings, the Seya-Namioka mounting serves admirably. The author has recently put into operation such a spectrometer at the $f/5$ focus of the 61-in. (155-cm) reflector of the Harvard College Observatory.[26] The grating is a Bausch & Lomb replica with a radius of curvature of only 11.5 cm and with 600 rulings/mm. The entire instrument including the RCA 1P28 photomultiplier and its cold box weighs less than ten pounds and fits into a carrying case the size of a bread box. The rather large width of the final spectrum (14 mm) presents no problem since it falls conveniently onto the 25-mm-long cathode of the photomultiplier. No field (or Fabry) lens is used to image the telescope objective on the photocathode in order to prevent guiding errors from producing an erratic output. The confusion disk seen by the photocathode apparently is large enough to smooth out minor driftings of the star in the entrance aperture.

The dispersion of the spectrometer averages about 100 Å/mm over the blue portion of the spectrum. On nights of average seeing a star image might be 0.1 mm in diameter making it possible to resolve 10 Å if the entire image is admitted. Use of a narrow entrance slit improves the resolution to slightly more than one angstrom unit. The blaze angle of the grating (7°35) puts the blaze wavelength at λ3600 Å, permitting the author and his colleagues to concentrate their studies in the region from λ5000 Å down to the atmospheric transmission cutoff near λ3200 Å. The ultraviolet transmitting envelope of the 1P28 photomultiplier has made it possible to operate at these short wavelengths. A photograph of this spectrometer appears in Fig. 2.

In some spectrometer mountings, particularly those where the angles of incidence and diffraction are not large, it might be possible to employ in some way the secondary or horizontal astigmatic focus produced by the grating. In such mountings this focus will fall on the side of the exit slit away from the grating. Its exact position can be calculated from an expression given by Beutler,[9] namely,

$$\frac{1}{r} - \frac{\cos\alpha}{R} + \frac{1}{r'} - \frac{\cos\beta}{R} = 0, \qquad (5)$$

where r and r' are the distances of the object and horizontal image from the grating center, respectively. The grating might image, for example, the telescope mirror or lens, thereby assigning the role of Fabry lens to the grating. Such a design would define and limit, of course, the usable values of α and β.

Seya-Namioka spectrometers are normally limited to a resolution of slightly less than an angstrom; therefore, there is never any need to use gratings with very large radii of curvature in this particular mounting. A high-resolution scanner can be best made using either a Paschen or a radius mounting. Whether the designer prefers to translate a large grating along the Rowland circle (radius mounting) or to move the exit slit and detector along this same circle (Paschen mounting) will decide between the two possibilities. Very high resolutions are possible, as we have already noted. Now the problems of astigmatism are no longer serious and much more latitude in design is possible.

Very recently the McPherson Instrument Corporation, Acton, Massachusetts, has developed a spectrometer which might best be described as a highly successful modification of the Johnson-Onaka mounting. Scanning is achieved both by rotating and translating the grating. Specifically, an arm is rigidly attached at one end to the grating and made to follow an accurately milled curve at the other. The grating is allowed to move (and rotate) along only one axis resulting in high resolution. In many ways it resembles the Eagle mounting, but its drive mechanism is simpler.

Ellipsoidal and Toroidal Gratings

That a concave ellipsoidal grating might be an excellent means of improving the final spectrum has been considered by Namioka.[21] Purcell and Tousey[27] have, in effect, used a toroidal grating; their method was to distort physically a focusing mirror into a toroidal shape and let the light thus focused fall on a spherical grating. However, at the present time gratings manufactured in these shapes are not generally available. In the hope that they will soon come on the market, a few words will be added illustrating their value.

Namioka[21] has reproduced a graph which shows strikingly the large decrease in astigmatism resulting from the use of an ellipsoidal grating in a Seya-Namioka mounting. Specifically, Namioka defines the semiaxes of the grating ellipsoid as a, b, and c. Semiaxis a is measured in the direction of the grating normal; b is the other semiaxis in the Rowland circle plane; c is perpendicular to the Rowland circle plane. With $c/b = 0.814$, and $R = b^2/a$, astigmatism will be zero at λ3800 Å and will increase slowly on either side of this wavelength until at λ6000 Å the width of the spectrum will be 0.03 times the length of the grating rulings. As mentioned earlier, the width of the same spectrum formed with a spherical grating would be about two-thirds the ruling length. Clearly, such an improvement in gratings would be of great interest to stellar spectroscopists.

The particular value of a is not critical in the above discussion. Therefore, toroidal mirrors can also improve the performance of a concave grating. A moderately thin grating blank mounted in a rigid holder with torsion screws at the top and bottom of the grating (above and below the Rowland circle plane) should produce the desired result.

It is hoped that ellipsoidal (or toroidal) concave gratings will be soon available at moderate prices. The spherical astigmatism is the only major disadvantage of concave grating spectrographs used for faint source analysis, and its elimination will make available to the experimental astronomer a dispersive component with even more potentialities than the spherical concave grating.

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A Birefringent Monochromator for Isolating High Orders in Grating Spectra

John W. Evans

A modified quartz Šolc filter, designed to isolate a single high order of a coarse grating, has proved to be a simple and convenient accessory for solar spectrography. It transmits unpolarized light, diminished only by absorption and reflection losses in the material, has a wide choice of bandwidth, and is tunable to any wavelength transmitted by the optical materials. This monochromator is used like an ordinary glass filter by simply placing it in front of the spectrograph slit. Its principles of operation and construction are described.

I. Introduction

The high orders of relatively coarse gratings ($\leq$300 grooves per mm) used at angles up to 70° are very useful in high dispersion solar spectrography because the unavoidable fluctuations in dispersion through the spectrum are smaller and there is more choice of dispersion at a given wavelength than with the finer rulings of low order. They are ordinarily difficult to use, however, because of the problem of isolating a single order. The use of a standard monochromator consisting of a spectrometer that images a spectrum on the spectrograph slit solves the problem quite thoroughly, but at the cost of a considerable light loss and some complication in setup and adjustment. The requirement that the monochromator be stigmatic within a Rayleigh limit or better usually calls for a fairly sophisticated optical system.

We have been using an adjustable birefringent monochromator at the Sacramento Peak Observatory for several months with very satisfactory results. The transmitted bandwidths can be varied (in discrete steps) from 180 to 550 Å at λ 8000 and 40 to 250 Å at λ 4000. The virtues of this device are high light transmission, stability, compactness (see Fig. 4), and simplicity of adjustment (if not of construction). It illuminates 30 mm of slit length with no lens system, and is simply placed in front of the spectrograph slit like an ordinary filter. The only readjustment in the telescope required is a change of 32 mm in focusing the solar image on the spectrograph slit to compensate for the added thickness of refracting material in the optical path. With the aid of glass filters near the spectrograph focal plane, two or three lines of interest in different grating orders can usually be photographed simultaneously—a matter of some importance in the study of spectroscopic changes in transient solar detail.

The birefringent monochromator is a folded quartz Šolc filter, modified to avoid the usual 50% light loss due to the initial polarization, and to provide accurate tuning of the wavelengths of the transmission bands.

The Šolc filter has been described in several places, but for convenience we refer to our own paper,[1] and adhere to the same notation. The initial matrix equations for the folded filter given there are incorrect.* Equation (10), for the transmissions of both the fan and folded filters, and the conclusions based on it, are correct, however.

Briefly, the folded Šolc filter consists of a pile of identical plane parallel birefringent elements, b, with optic axes parallel to their surfaces. [See Fig. 1(a).] In a filter of n elements, the alternate elements are oriented with their optic axes at angles of plus and minus $\alpha/2 = \pi/4n$ to a fixed direction, x, perpendicular to the instrumental axis, z. The pile is placed between two polarizers, p (usually Polaroid sheets). The first polarizer may be oriented to transmit the electric vector either parallel or perpendicular to the x direc-

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* The expressions for both the odd and even forms of the folded filter should be

$$\begin{pmatrix} E_{xn} \\ E_{yn} \end{pmatrix}_{\text{Folded}} = i^n P_y S \left(\frac{\alpha}{2}\right) [S(-\alpha)G]^n S \left(-\frac{\alpha}{2}\right) P_x \begin{pmatrix} E_{x0} \\ E_{y0} \end{pmatrix}.$$

$$G = \begin{pmatrix} e^{+i\gamma} & 0 \\ 0 & e^{-i\gamma} \end{pmatrix}.$$

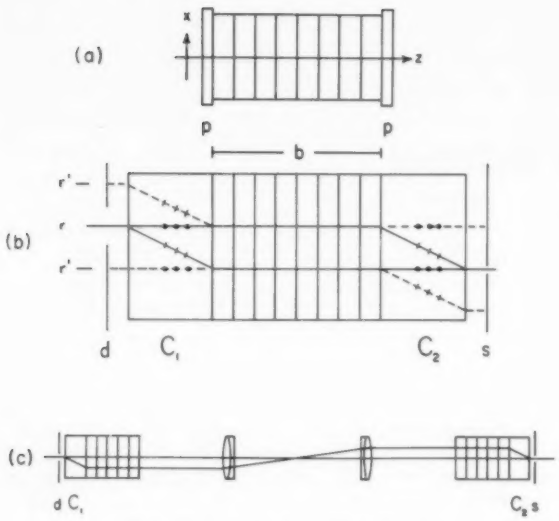


Fig. 1. (a) Šole filter, consisting of birefringent elements, b, placed between two polarizers, p. (b) The same filter with calcite prisms, C, used as polarizers to utilize both polarized components into which the incident light is divided. (c) Schematic diagram of filter and lens system combined to accommodate large focal ratios.

tion, and the second polarizer is crossed with respect to the first. The spectrum transmitted by the assembly consists of a series of widely spaced sharp maxima, analogous to the orders of a grating.

II. Device for Preserving All of the Incident Light

The first polarizer of the filter of Fig. 1(a) eliminates half of the incident light. Contrary to the usual impression, this is a serious loss for a solar spectrograph in spite of the great brightness of the source. The light traversing a 50-μ slit may be spread out into a spectrum 50 to 100 m long between 3500 and 9000 Å, and exposure times sometimes go to 30 or 40 sec, during which quite significant changes in solar detail often occur.

The first modification introduced in the birefringent monochromator avoids the polarization loss by the use of identical and parallel calcite prism polarizers, C_1 and C_2, with end surfaces parallel to the cleavage planes, as shown in Fig. 1(b). An unpolarized ray of light, r, is divided by C_1 into an upper and lower ray with electric vectors perpendicular and parallel to the x direction. After traversing the pile of birefringent elements the wanted light (in the filter transmission bands) in each of these rays emerges with its electric vector at right angles to its direction on entering the pile. The unwanted light (between the transmission bands), on the contrary, emerges with its electric vector parallel to its direction on entering the pile. Hence, after traversing the pile, the unwanted light in the upper ray traverses C_2 without deflection, while the wanted light is deflected downward as shown in Fig. 1(b). Similarly for the lower ray, the wanted light is undeflected by C_2 and the unwanted light is deflected downward. Thus a slit, s, placed as shown, is illuminated by the transmission bands from both the upper and lower rays, which combine to give unpolarized light, while the unwanted light between the bands is intercepted by the slit jaws. The only loss in the wanted light is that due to absorption and reflections in the filter material.

Unfortunately the slit also accepts unwanted light from rays r′. It is therefore necessary to place a diaphragm, d, immediately in front of C_1 to intercept these rays, a necessity which strictly limits the field in the x direction. If the monochromator is placed in the convergent beam immediately in front of the spectrograph, the requirement is that in the plane of diaphragm d, the aperture of the beam centered on ray r be definitely separated from that centered on r′. The diaphragm can then intercept the light cones centered on r′ completely without vignetting the desired beam centered on r. The angular separation of the two rays in calcite is 0.109 radian. The minimum thickness of C_1 and C_2 required to accomplish the separation is approximately:

$$t_c = \frac{\alpha' t_b + s'}{0.109 - 2\alpha'}, \qquad (1)$$

where

t_c = thickness of C_1 (and C_2),
t_b = thickness of everything between C_1 and C_2,
α' = average angular diameter (focal ratio) of the converging beam in the material of the filter,
s' = slitwidth plus total expansion of the beam in the air paths between s and d.

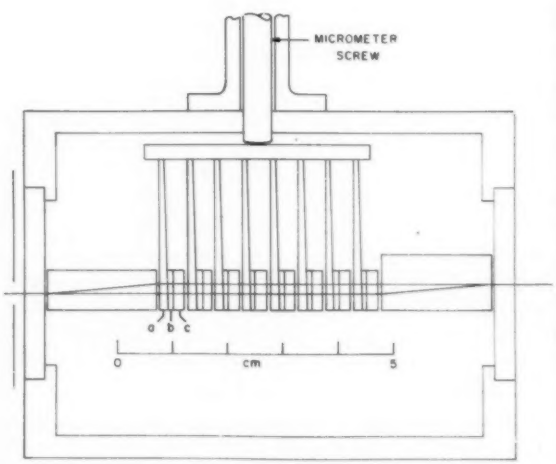


Fig. 2. Diagram of the tunable birefringent monochromator. The optical parts are shown to scale.

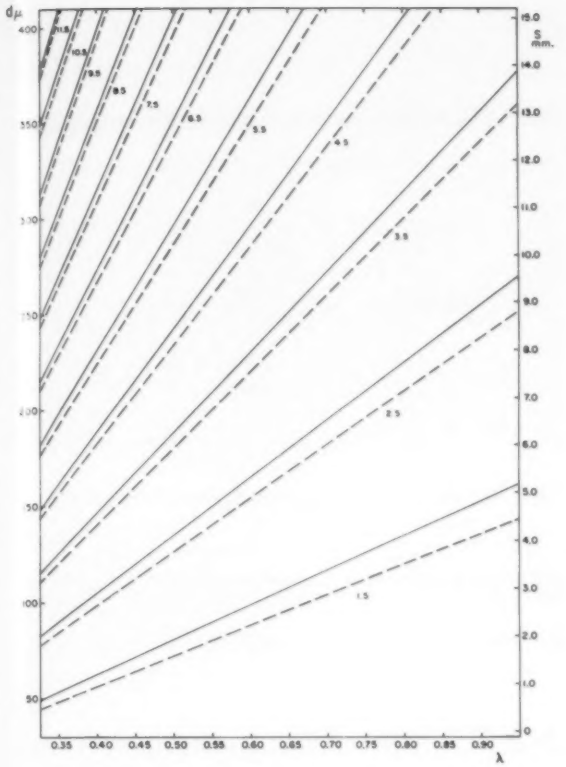


Fig. 3. Relation between the wavelengths of transmitted bands and element thickness, d, in microns (shown on the left) and the corresponding scale setting, S, on the millimeter micrometer of the monochromator.

Most high dispersion spectrographs have focal ratios in air of less than $f/35$, which leads to reasonable lengths for the calcite prisms. Much faster systems require some more sophisticated polarizing beam splitters to achieve greater separations, or an optical system which reimages diaphragm d on the slit. The latter is independent of focal ratio, and the required separation of the rays is only a little more than the slitwidth. Figure 1(c) shows one of a number of possible versions of such a system.

III. Wavelength Tuning

In the birefringent monochromator with calcite prisms, the transmission is double that of the original Šolc filter and Eq. (10) for the transmission from out earlier paper becomes

$$\tau = t\left[\frac{\sin n\chi}{\sin\chi}\cos\chi\,\tan\alpha\right]^2, \qquad (2)$$

where t represents the absorption and reflection losses and χ is defined by the relation $\cos\chi = \cos\gamma\,\cos\alpha$. Here $\gamma = \pi(\eta + {}^1/_2)$, where $\eta = d(\epsilon - \omega)/\lambda$ is the wavelength retardation in a single birefringent element of thickness d. The principal transmission bands occur at wavelengths for which $\eta + {}^1/_2 = k$, an integer, and the adjacent transmission zeros at $\eta + {}^1/_2 \approx k \pm 0.87/n$, where n is the number of birefringent elements in the filter. The corresponding wavelengths follow with sufficient accuracy from the empirical relation, $\lambda/(\epsilon - \omega) = a\lambda + b$, pointed out by Šolc. Through the visible region $a = 120.0$, $b = -6.11$ (λ in microns) for crystal quartz. Thus $\eta = d/(a\lambda + b)$, from which we find:

$$\lambda_\eta = \frac{1}{a}\left(\frac{d}{\eta} - b\right) \text{(wavelengths of transmission bands)}, \qquad (3)$$

$$\lambda_\eta - \lambda_{\eta+1} = \frac{1}{\eta + 1}\left(\lambda_\eta + \frac{b}{a}\right) \text{(band separation)}, \qquad (4)$$

and

$$\delta\lambda_\eta = \frac{0.87}{n\eta}\left(\lambda_\eta + \frac{b}{a}\right) \text{(bandwidth)}, \qquad (5)$$

where $\delta\lambda$ is the wavelength difference between the center of a transmission band and the first zero on either side, or the effective bandwidth.

The wavelength of a given order η can be controlled by adjustment of d, according to Eq. (3). In the Sacramento Peak monochromator each of the 8 quartz elements is in the form of a complementary pair of wedges one of which is adjustable with respect to the other. The arrangement will be evident in Fig. 2, where the components of a single element are labeled a, b, and c. Since it was necessary to use orders as low as $\eta = 1.5$ at λ 3500, the total thickness of the two wedges, a and b, of a given element would have to be only 54 μ at the thin setting. In order to avoid the problem of making and mounting such thin quartz elements, a compensator, c, was used in the form of a plane parallel element of quartz with its optic axis perpendicular to that of the wedge pair. The effective thickness, d, is then the difference in thickness between the compensator and the sum of the two wedges at a given setting. The a components of all eight elements move as a single unit in the vertical direction to adjust d through a range of 50 to 380 μ.

The optical assembly is contained in an aluminum tank with glass (or quartz) end windows, filled with mineral oil to reduce reflections from the various elements.

The graph of Fig. 3 shows the calculated relation between the thickness, d, and the wavelengths of the transmission maxima for successive orders (where $\eta + {}^1/_2$ is integral). The wedges are adjusted as a unit by a micrometer screw for which the scale reading, S (in mm), is $S = 0.04031d - 1.331$. The S scale is shown on the right in Fig. 3.

The assembled monochromator mounted in front of the slit plane of the spectrograph at the Sacramento

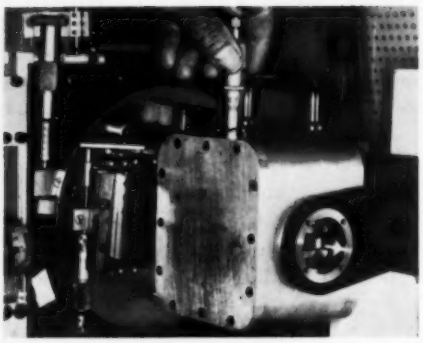


Fig. 4. Birefringent monochromator mounted before the slit of the Sacramento Peak spectrograph. The initial diaphragm, *d*, has been removed, and the first four elements are visible through the aperture.

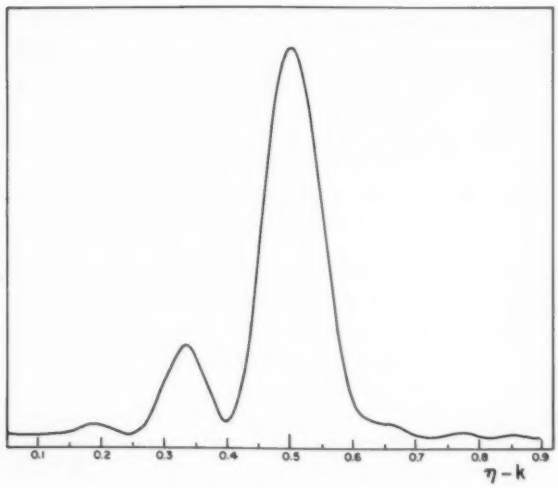


Fig. 5. Measured transmission of the monochromator as a function of $\eta - k$, where k is an integer. The transmission maximum is 0.86.

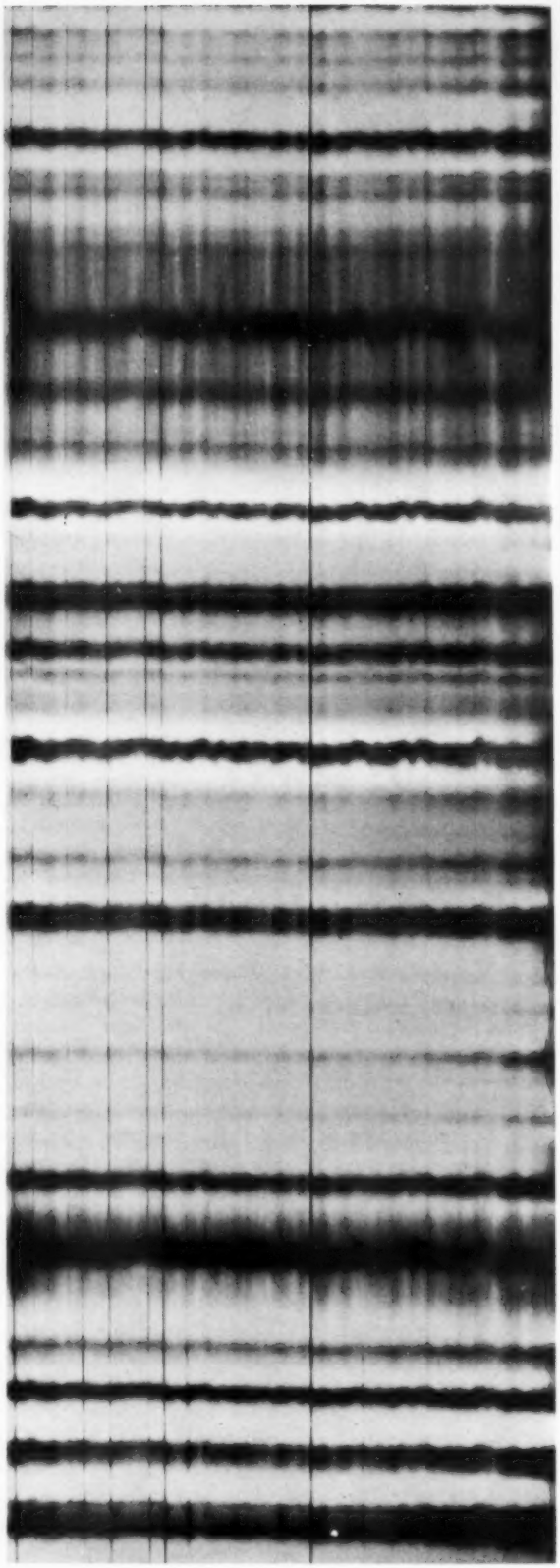


Fig. 6. Solar spectrum taken through the monochromator and the 13-m spectrograph with a grating of 300 grooves/mm. The "wiggles" in the lines are due to Doppler shifts in the regions of the sun imaged along the slit, and are observable only in a perfectly stigmatic system. The original width of spectrum across dispersion was 24 mm.

Peak Observatory is shown in Fig. 4. The dimensions of the case are 12 × 13 × 9 cm. A hinge on the mounting bracket permits the whole unit to swing up out of the optical beam when not in use. The transmitted beam illuminates a 3 cm length of slit. The focal ratio (in air) of the entering light is $f/70$, but the monochromator will accommodate beams up to about $f/50$.

As presently adjusted this instrument departs markedly from the theoretical performance in the wavelength intervals between the principal maxima. Figure 5 shows the transmission curve measured photoelectrically. The presence of a strong 16% secondary (integrated) on the long wavelength side of each band is very conspicuous. Its location with respect to the principal bands is shown by the dashed lines in Fig. 3. We have not been able to determine the cause of this abnormal secondary. The η's for the eight elements are the same within 0.05, and the orientation of the optic axis in each was set correctly within the accuracy of an x-ray goniometer, about 10′. In any event, this strong secondary has not proved to be a serious matter in actual use. At any wavelength in a given order of the grating, one has a choice of several suitable monochromator settings, and it has always been possible to select at least one which quite effectively suppressed the unwanted grating orders. The most troublesome region is, quite naturally, the violet and ultraviolet, where grating orders are close together. However, with the aid of an auxiliary glass filter (Schott UG-5), excellent spectra in the 15th order of a 300 grooves/mm grating have been obtained at λ 3850. Such a spectrum, taken for the purpose of showing the local Doppler shifts in the Fraunhofer lines, is shown in Fig. 6.

The birefringent monochromator has two distinct limitations for use in solar spectroscopy, even if its transmission curves are indistinguishable from theory. The suppression of unwanted orders of a grating is generally not complete, and the contamination may amount to a few percent of the unfiltered brightness. Hence line profiles may require an inconvenient correction (which, however, is easily determinable by experiment). Finally, the transmission bands are not flat-topped, and the variation of transmission over spectra longer than about 0.2 of the bandwidth, $\delta\lambda$, requires correction for accurate photometry. For many purposes, however, the monochromator is a highly satisfactory device for high dispersion spectroscopy, with the great virtues of simplicity and certainty of adjustment, and negligible light loss.

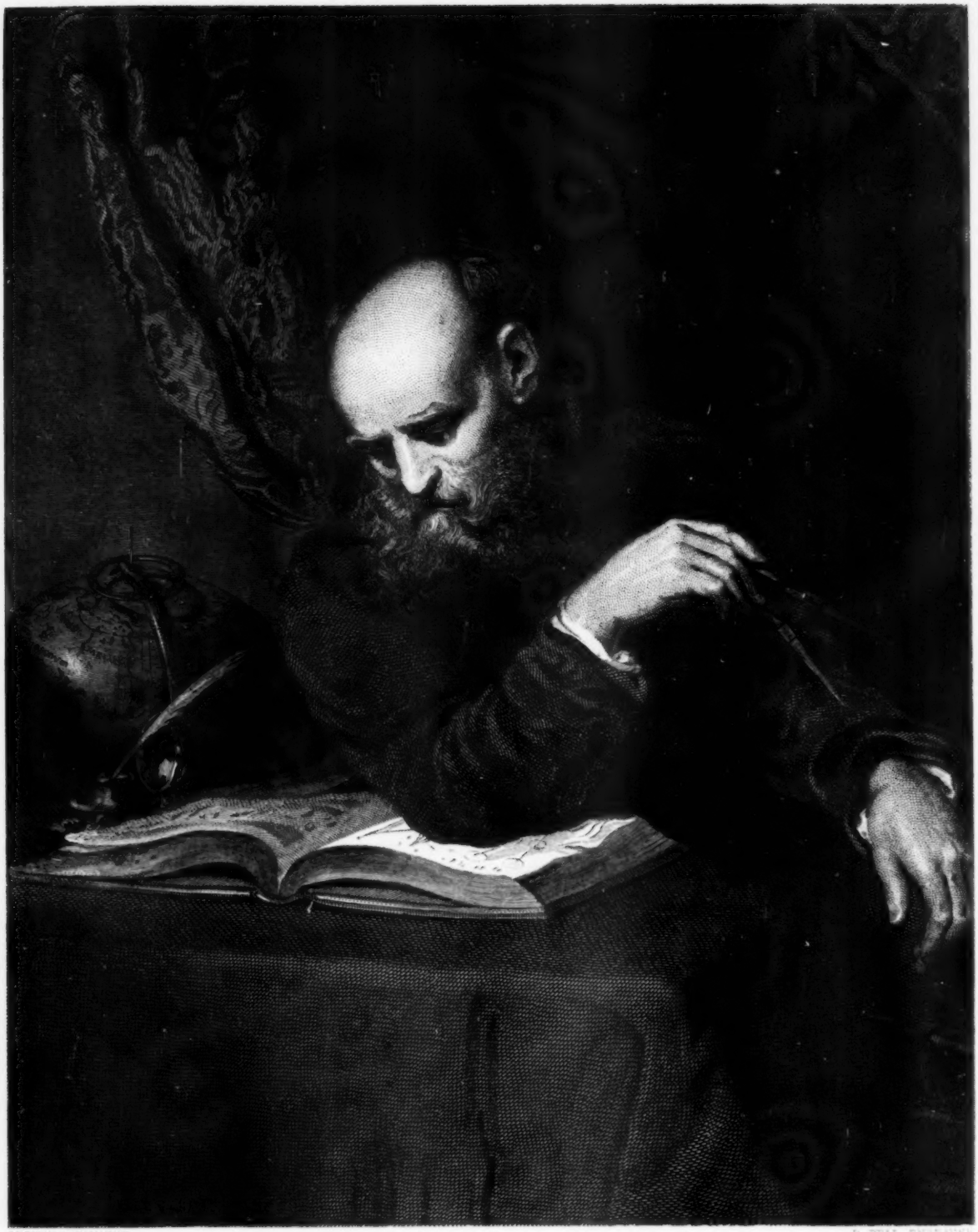
The Sacramento Peak monochromator was constructed by the Rocky Mountain Instrument Company, who should be complimented for their excellent optical and mechanical workmanship. It is a pleasure to acknowledge with thanks the careful photoelectric measurement of the transmission curves by Ian Elliott, a visitor on leave from the Dunsink Observatory.

References

1. John W. Evans, J. Opt. Soc. Am. **48,** 142 (1958).

Special Summer Courses in Infrared Spectroscopy—Massachusetts Institute of Technology June 17–28, 1963

Two intensive courses on infrared spectroscopy (Technique, June 17–21, and Applications, June 24–28) will be offered by the Massachusetts Institute of Technology during the summer of 1963. The courses will be in charge of Dr. Richard C. Lord, Director of the Institute's Spectroscopy Laboratory, and Dr. Dana W. Mayo, Lecturer in Chemistry, and visiting lecturers will include Dr. F. A. Miller, Mellon Institute, Professor E. R. Lippincott, University of Maryland, Dr. L. J. Bellamy, British Ministry of Aviation, and Professor E. R. Blout, Harvard University. Application forms and full information may be obtained from Dr. J. M. Austin, Director of the Summer Session, Room 7–103, Massachusetts Institute of Technology, Cambridge 39, Massachusetts. The program on Technique of Infrared Spectroscopy will comprise thirty hours of lectures and laboratory work, integrated to give comprehensive instruction in both theory and practice. The lectures will deal with the fundamental optics of infrared spectrometers and the factors determining their design and performance, infrared spectrophotometry, qualitative and quantitative analysis, and techniques for the preparation of samples for spectroscopic study. Afternoon laboratory work designed to introduce the student to the practical side of these topics will be carried out in small groups with the extensive infrared instrumentation of the Spectroscopy Laboratory, augmented by the most recent instruments loaned by the manufacturers of infrared equipment. The work will be supervised by experienced personnel both from M.I.T. and from the manufacturers. The second program, Applications of Infrared Spectroscopy, will consist of lectures by staff and guests on theoretical aspects of the interpretation of spectra, on group frequencies and integrated intensities, and on applications of infrared and other spectroscopic methods to the solution of chemical research problems. Afternoon hours will be devoted to practice, in small groups closely supervised by the staff and visiting lecturers, in the interpretation of the infrared spectra of complex molecules. Lecture, laboratory and conference rooms used for the program are completely air-conditioned. Participants may reserve rooms in the Institute dormitories and all other Institute facilities will be open to them.



M. WYATT, PAINTER.

The Astronomer
from the picture in the Vernon Gallery

Low Sun Phenomena

W. A. Feibelman

Of the many natural effects of atmospheric optics,[1] none seems to have been given as much attention as the "Green Flash."[2] Lately, a man-made effect has been added to the list of phenomena: artificial prominences of the sun caused by airplanes crossing the sun. Because of the increasing importance of observations of solar flares and prominences, discrimination between natural and artificial effects is desirable. Öhman[3] recently observed a bright solar prominence which could not be correlated with other solar observations and he concluded that it was caused by the glowing exhaust gases of a jet aircraft. He then asked the Swedish Air Force to fly planes in front of the sun while visual observations were made and thus confirmed his earlier observation of limb prominences, but no photographs seem to have been attempted. During routine observations of the sun in the past four years, the writer has obtained dozens of photographs of these artificial prominences.[4] Only modest optical equipment is required and some of the results are shown in the accompanying photos. A 5-cm diameter achromat of 127-cm focal length is used without filter on a Leica camera with reflex viewing attachment. Exposures vary with sky conditions but usually $^1/_{200}$ sec is used for Panatomic-X film. Numerous photographs of green and red flashes have been obtained on black-and-white as well as on Kodachrome film when the sun was from 20° above the horizon to near setting. The cause of these flashes is known to be due to atmospheric dispersion, absorption, and scattering. They can be used reliably to predict the astronomical seeing for the night: the better the green flash, the worse the seeing will be. The three frames of Fig. 1 illustrate the development of a green flash, taken at intervals of about 2 sec. (The dark streak is a thin cloud layer.)

Inasmuch as the Greater Pittsburgh airport lies some 30 km to the west of this observing site, it happens quite frequently that a variety of aircraft crosses the field of view, giving rise to artificial limb prominences. The effect is particularly strong for jets but is caused by other planes, too. Figure 2 shows a DC-6 producing an artificial green flash of brilliant color. From the known dimensions of the planes and apparent angular diameter of the sun one can calculate that these effects are of a very local origin, varying in distance from 5 to 80 km.

Figures 3 to 6 show a flight of three F-86 jet fighters during takeoff (4 and 5 showing the "ingress" and "egress" of the same plane). The exhaust plumes are particularly bright during take-off, possibly due to water injection, and on the original negatives their segmented form resembling shock waves is clearly shown.

In Fig. 7 a DC-6 (or DC-7) produced a bright red trail while climbing into the sun. Figure 8 shows the exhaust plume of a French-built twin-jet "Caravelle" which missed the sun. The four-engined jet liner in Fig. 9 left a frayed edge on the right limb while producing another prominence on the left. Figures 10 to 13 show various aspects of "Constellations" similar to the preceding exposures. In Fig. 13 the engines produced four miniature suns, complete with green color above and red below. High-speed movies and spectra of these effects may give new atmospheric data and their comparison to rocket "signatures" may be of interest.

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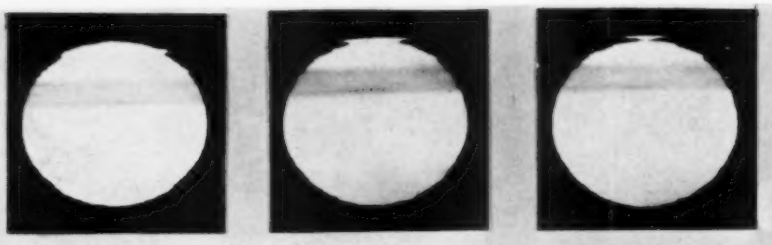
Received 27 August 1962.

Overleaf shows photographs of natural and artificial low sun phenomena.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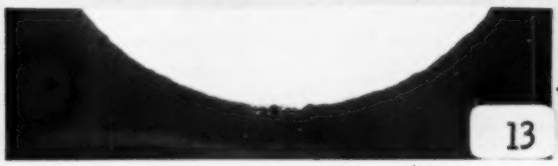
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Optical Design for Two Telescopes

Part A. A Baker-Type Off-Axis f/0.35 Solid Schmidt Camera

Part B. An f/5 Solid Telescope

Arthur S. De Vany

Part A. Making a Baker-Type Off-Axis f/0.35 Solid Schmidt Camera

Introduction

A solid off-axis Schmidt camera of the Baker-type has been made.[1] This solid Schmidt camera has three deep, aspheric surfaces of the form used on correcting-plates of ultrafast systems. For the cemented surface, mating positive and negative aspheric correcting-surfaces are needed. For all aspheric surfaces the clear aperture for the cameras constructed was 57-mm diam. The depths at the 0.88 neutral zones on the correcting plates were over 2.5 mm. The difficulties of working on small apertures, combined with large aspheric departures, are well known to the optician.

Optical Fabrication Techniques

At the start in making the off-axis Schmidt, it was decided to make a conventional on-axis Schmidt because the optical working techniques would be easier than in the case of the laminated, solid off-axis Schmidt (Fig. 1). Later on, it proved not to be necessarily so, for the working techniques turn out to be essentially the same for both on-axis and off-axis Schmidt cameras. The several steps needed in making the conventional on-axis and the special off-axis Schmidts can be summarized as follows: the main body is composed of two DF-2 flint glasses, which are cemented together, and a dense barium crown glass cemented in turn on the flint body.

It can be seen in Fig. 1 that there are two different forms of aspheric surfaces. The first involves the surface to be cemented on the main flint body to be matched by the corresponding surface on the barium crown element, and the second is the other side of the barium crown element, which is an air-surface and the first surface of the final assembled system. The two aspheric shapes are similar in form but different in depth and have been arrived at from calculations supplied at an earlier date by Baker.

The bottom section of the flint body with its 2.213 in. (56.21-mm) primary spherical mirror and the 1.224-in. (31.09-mm) spherical focal surface, and its flat surface were made and tested with test plates. All were worked to $^1/_8$th of a fringe surface quality. All three surfaces were centered to a common axis by not more than 0.025 mm of wedge.

The second part of the flint body (see Fig. 1, dashed lines for the on-axis type), or top piece, was made next. The hole shown in Fig. 1 was core-drilled to within 0.8 mm of the inner face. After the outer aspheric surface was finished, this flint section of the body was easily brought to the proper thickness and concentricity to within 0.025 mm. The plug previously cemented into the hole with pitch was removed in solvents upon completion of the aspheric surface.

In order to make the matching correcting surfaces for the respective surfaces of the DF-2 body and adjacent thin dense barium crown disk, two sets of tools were fabricated. The first set was made up from Meehanite cast iron, and the second from medium hard brass. The aspheric surfaces of both Meehanite and brass tools were first formed on the lathe by use of the "cross-feed" and the "feed-in" slide. This operation gave a rough surface which was brought to approximate form by scraper and emery paper. The final values for the x and y coordinates of the aspheric surfaces were measured with the aid of dial indicators. The y-values were read from an Ames indicator reading to 0.0005 in. (0.013 mm). The x-values were read by means of a very precise Metron indicator reading to 0.0001 in. (0.0025 mm) with estimates to one half of a ten-thousandth and having a travel of 0.200 in. (5.1 mm). The surfaces of the cast iron tools were brought to

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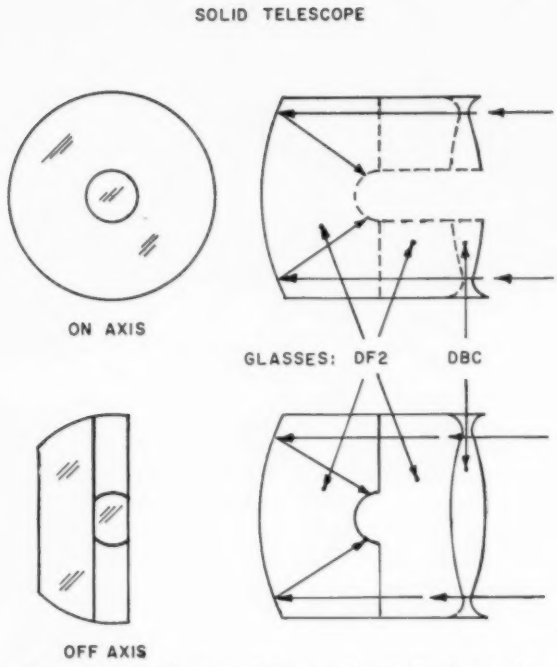

Fig. 1. Schematic views of the on-axis and off-axis Schmidt cameras.

within 0.025 mm of the final form of the aspheric surfaces. The corresponding surfaces of the brass tools were within 0.0025 mm. The indicator for the x-coordinate must have a hardened ball no larger than 0.8 mm to prevent a reading error in measuring the sagitta of either the concave or convex surface.

The grinding of the corrector plates was carried out with #320 carborundum with the parallelism constantly maintained and checked. The cast iron tools departed by 0.025 to 0.050 mm in the roughing and fine-grinding emeries through aloxide #95. The brass tools were used only to clean up and shape the aspheric surfaces to their final form. The final form of the aspheric surfaces on the corrector plates was ground into shape in two aloxide #50 wets of five minutes duration.

The fine-ground surfaces did have several high rings apparent in them when first observed. It was felt that these would work down at first, and then blend into the surface when fully polished. The polisher was made on a base of a small-pore sponge rubber which did not spring as readily as some of the larger-pore sponge rubber. Polishing pitch was poured onto the sponge rubber cut to a diameter of the same size as the optical surface to be polished.[2] The pitch polisher was formed and then cut into $^3/_8$-in. (9.5-mm) squares with each square separated from the adjacent squares. The polisher looked rather horrible at the end, being full of cracks, chips, etc. However, it is the opinion of the writer "that the world's worst-looking optical tool does the world's best work." This was all handwork and very little side motion was used.

The other side of the corrector plate of thin dense barium crown of 1.27 mm thickness at the neutral zone was fine-ground and polished, as previously described for the aspheric surface on the main flint body. It should be noted that the final form on the top surface of the barium crown is the controlling surface for the quality of the final image.

The mating brass grinding tools of the final aspheric form must be lapped together almost dry with no abrasive between them, and checked in two directions at 90° intervals by means of the indicators. One attempt to use a poor grade of cast iron for finishing showed hard spots, and could not be brought to the final necessary aspheric shape. The only figuring found necessary after testing was to cure a high center. This was brought down quickly with a smaller polisher.

Testing

Several methods of testing were used on the solid camera while it was being optically figured, and when it was finally finished.

A. Lower's Test[3]

This test was the first one used. A ruled line 0.05 mm wide was ruled barely through a semidry lacquer paint across the focal surface. This gave a projected line across the aperture that could be observed with a small telescope. The line could be displaced to observe at any other zone by moving to a different position for observation. The observer must not make any observations with the unaided eye because of the disturbing effect caused by the strong aspheric front surface. (See Fig. 2.)

B. De Vany's Test[4]

This test in many respects is the same as Lower's but is a refinement in that it projects a series of ruled squares that can be observed through a telescope or projected on a screen some distance away. To do this,

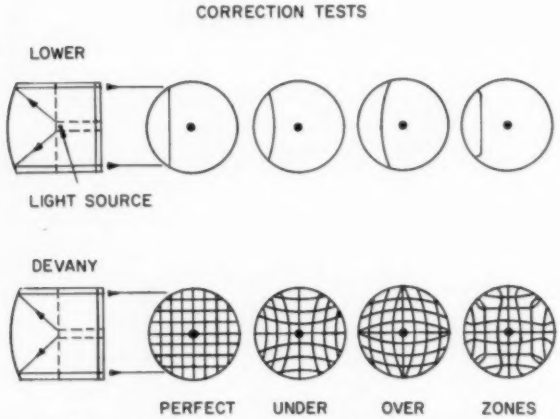

Fig. 2. Nature of Lower and De Vany test procedures.

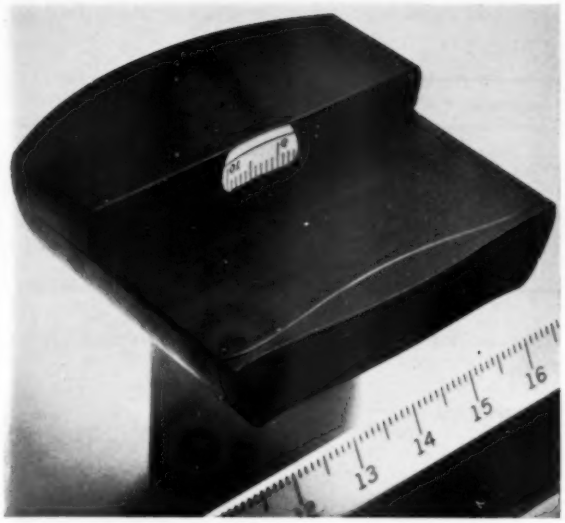

Fig. 3. A front view of the $f/0.35$ solid Schmidt camera.

a halftone engraving from a clear white photoprint of 150 squares per inch was used. Generally, a white section of a photoreproduction of any white section in a printed photograph can be used. A small sector of the photoengraving covering about a 3-mm section of focal plane was pasted onto the spherical curve with a drop of kerosene. A microscope illuminator lamp was placed over the hole. The image thus projected was 1 m in diameter. A multiple series of squares was observed, making it possible to follow the contour of the figuring. (See Fig. 2.)

Optical Bench

The image was examined on an Askania optical bench through a 20× microscope equipped with a right-angle prism. Without any diffusing screen, the observer was thus able to view the image on the focal surface formed by the solid Schmidt of a light source subtending one second of arc in a collimator. The image measured approximated an Airy disk about 0.0075 to 0.0100 mm diam. The finished system is shown in Figs. 3 and 4.

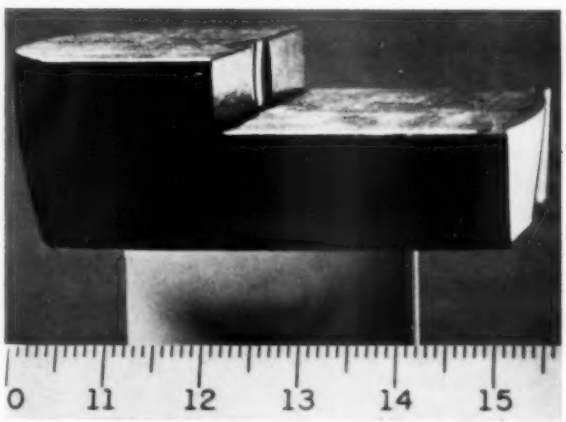

Fig. 4. A side view of the $f/0.35$ Schmidt camera.

Conclusions

We may draw the following conclusions:

1. The optical working techniques of an on-axis solid Schmidt system and of an off-axis Schmidt system are the same.
2. The fabrication of the aspheric surfaces is entirely dependent upon the final form on the brass lapping plates.
3. The abrasive used in the last grinding before polishing must be broken down so that there is relatively no film thickness existing between the lapping tool and the correcting plate.
4. The Lower and De Vany tests are used to detect high and low areas which are sources of zonal spherical aberrations.

We are grateful to James G. Baker for the basic design and to Jack Raquet for making the aspheric lapping plates.

Part B. An $f/5$ Solid Telescope

A solid glass telescope of the Cassegrainian type has been made. Both mirror surfaces are spherical, and the correction for spherical aberration for the system is effected by means of a weak aspheric correction on the front surface of the system. The focal plane is taken to be coincident with the central or vertex region of the primary mirror. Several cylindrical baffles to eliminate glare light were core drilled in the solid body. (Fig. 5.)

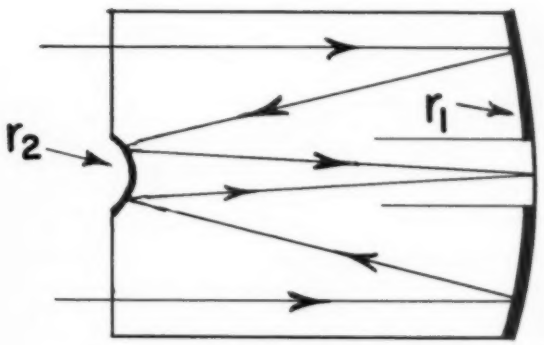

Fig. 5. Solid Cassegrain telescope.

$f' = 207.26$ mm
diam. $= 44.98$ mm
$r_1 = 134.19$ mm
$r_2 = 48.26$ mm
Glass type, BSC-2
$N_D = 1.517$
$L'' = 50.35$ (thickness of the glass body from the secondary's surface to the surface of the primary mirror)

It is well known that the best correction for geometrical optics requires that the neutral zone of the aspheric correcting surface be placed at the 0.86 zone; and for the minimum of glass removal and for best correction in diffraction optics at the 0.707 zone. In this instance, a compromise between image quality and methods of fabrication together with the fact that there is an appreciable central obscuration caused the neutral zone to be placed at 0.8. The radius of curvature for the primary mirror is 134.193 mm, and for the secondary mirror, 48.26 mm. Five rays have been traced through the system for the on-axis image and zone by zone give the following results:

Zone height Y (mm)	Back focus (mm)	Zone height Y (mm)[a]	Back focus (mm)
21.59	50.3588	10.00	50.3494
20.32	50.3577	5.34	50.3486
17.297	50.3651	LA_m[b]	0.104394

[a] Y is the zone height and is related to y which is the aspheric zone height and x the sagitta depth.

[b] The difference in the back focal length or the amount of spherical aberration from the outer zone and the inner zone.

The x and y values of the aspheric correcting surface are listed below.

y (mm)	x (mm)	y (mm)	x (mm)
2.54	0.00010	15.24	0.00219
5.08	0.00038	17.297	0.00231
6.35	0.00058	17.78	0.00230
7.62	0.00081	20.32	0.00197
10.16	0.00131	21.59	0.00158
12.70	0.00181		

The coma for one degree half-field is approximately 68 arc sec.[5]

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5. B. Schmidt, "A Rapid Coma-free Mirror System, Hamburg Observatory," Amateur Telescope Making, Vol. 3 (Scientific American Publishing Co., New York, 1953), p. 354.

Information for Contributors

Scope: Papers are welcomed in the broad areas of applied optics, in disciplines related to optics and employing optical techniques. Papers should be sent to *The Editor, APPLIED OPTICS, 1155 Sixteenth St., N.W., Washington 6, D.C.* Manuscripts may be submitted in English, French, German, or Russian, and the presentation should be as succinct as comprehension will permit. In general, the metric system of units is preferred. One original and one carbon copy of the manuscript, with two sets of all illustrations, must be sent in. Manuscripts should be typed double or triple spaced on one side of 22 × 28 cm (8½ × 11 in.) paper, leaving a 3.8 cm (1½ in.) margin all round. Papers on the more fundamental aspects of experimental and theoretical optics should be sent to *The Editor, JOURNAL OF THE OPTICAL SOCIETY OF AMERICA, National Bureau of Standards, Washington 25, D.C.*

An **abstract,** adequate as an index and a summary, of not more than 100 words should appear at the beginning of the paper after the *title, author's name, affiliation, and address.* In the case of papers in a non-English language, they must be accompanied by an abstract in English as well as an abstract in the language of the paper. It should be borne in mind that this abstract may be used in toto by the abstracting journals, therefore it should be self-contained.

Figures suitable for printer's use should be sent. Bear in mind that illustrations will normally be reduced to column width (8.4 cm—3⅜ in.—20 picas). *Halftones:* two sets of glossy prints are needed, which should be mailed flat, with any proportion or framing indicated on a working copy. *Line drawings* should be suitable for reproduction and be not larger than 22 × 28 cm (8½ × 11 in.). *Captions* should be listed on a separate sheet in addition to each caption appearing on each illustration.

Tables should be typed on separate sheets and the data therein be intelligible, by title, without reference to the text. Tables should include a minimum of vertical ruling.

References must be typed on a separate sheet, be numbered consecutively in the order of their appearance in the text, and follow this form:

1. F. C. Brown, Phys. Rev. **12,** 345 (1821).
2. J. Culpeper, *Space Optics* (Georgetown Institute of Technology Press, Washington, D.C., 1861), pp. 12, 345.

A list of abbreviations for the names of journals is published in the *Chemical Abstracts List of Periodicals 1961.* To make for uniformity of presentation generally, the *AIP Style Manual,* second edition, should be used. In general, *APPLIED OPTICS* differs from the *Style Manual* only inasmuch as footnotes appear at the bottom of the page of text, while references are listed numerically at the end of the paper.

Letters to the Editor should follow the above suggestions, but no abstract is required.

Nine-Channel Polychromator for Observation of Time-Dependent Spectral Line Profiles

George R. Spillman,* William S. Cooper, III, and John M. Wilcox

The instrument (polychromator) described observes time-dependent spectral-line profiles by simultaneous measurement at nine different wavelengths of light intensity as a function of time. A cylindrical lens magnifies the dispersion of a Jarrell-Ash Model 82000 Ebert Monochromator and forms an image on a light-pipe holder. Light pipes transfer light from various sections of the image—i. e., different wavelengths—to photomultiplier tubes, and the responses are displayed on oscilloscopes. The instrument has been used to look at total wavelength spans of 15 Å and 20 Å.

Introduction

This instrument (polychromator) is designed to provide time-dependent profiles of broadened spectral lines. It measures light intensity as a function of time at nine closely spaced wavelengths simultaneously. The primary purpose of this instrument is to provide a means of measuring the ion density in a decaying hydrogen plasma of 10^{15} to 10^{16} ions/cm^3 by observation of the Stark-broadened hydrogen emission lines. Similar instruments have been constructed in other laboratories.[1-3]

The instrument uses a Jarrell-Ash Model 82000 Ebert Monochromator with the exit slit removed (see Fig. 1). The linear dispersion of the monochromator is 16 Å/mm.

To provide additional linear dispersion, a cylindrical lens with its axis parallel to the entrance slit is used (a spherical lens would give unwanted magnification parallel to the slit). An image of the entrance slit is formed in the plane of the removed exit slit. Light from this image passes through a 9.5-mm wide slot in the face plate of the monochromator, through the cylindrical lens, is reflected over the top of the monochromator by two plane mirrors, and finally is focused on a light-pipe holder 130 cm from the cylindrical lens. The mirror arrangement makes the instrument more compact. The light from the monochromator diverges in the direction parallel to the slit at the acceptance angle of the monochromator but is imaged (with magnification) in the direction perpendicular to the slit. Light from nine sections of the image (corresponding to nine different wavelengths) enters light pipes and is carried to 1P21 photomultiplier tubes. The responses are displayed on oscilloscopes.

The Lens

The cylindrical lens is a polished cylinder of Plexiglass. This shape was chosen rather than a thin lens primarily for ease in construction. To provide means of focusing and aligning, the lens is mounted on a microscope stage which is attached to the front plate of the monochromator. The final linear dispersion may be changed by installing a lens of different diameter. Lenses 3.73 and 2.85 cm in diameter have been used, giving final linear dispersions of 0.34 and 0.26 Å/mm, respectively.

Focus is achieved by using white light and the zero-order image of the diffraction pattern. Since the wavelength drive of the monochromator is not designed to reach zero order, the wavelength drive arm must be disconnected and moved by hand to zero order. Chromatic aberration is quite noticeable, but has not affected focusing enough to cause serious loss in resolution.

Light Pipes

The nine light pipes are 1.6-mm thick Plexiglass and are 10 cm high at the entrance end (approximately the height of the image formed by the cylindrical lens). They taper to 1.6 cm at the phototubes. In most of our use so far, the light pipes have been spaced nonuniformly but approximately symmetrically about the center light pipe, with a separation of 5.75 cm between outermost light pipes. The spacing of the light pipes may be varied, giving additional flexibility to the instrument.

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* 1st Lt., U.S. Air Force. The opinions expressed by the Air Force author are his own and do not necessarily reflect those of the United States Air Force or of the Department of Defense.

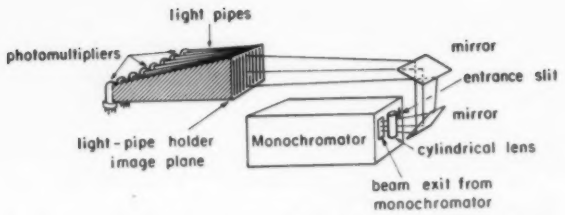

Fig. 1. Schematic drawing of the polychromator. Light from the monochromator is imaged on the light-pipe holder by the cylindrical lens; nine light pipes carry light of nine different wavelengths to the photomultipliers.

Resolution

The monochromator forms a curved image of a straight entrance slit, and the curvature is dependent on the wavelength setting of the monochromator. To maintain wavelength resolution the slit is stopped vertically, so that a relatively straight portion of the image is used. In our work with the polychromator a spherical lens is used to image an extended plasma light source on the entrance slit. Stopping the slit vertically selects a small portion of the image, hence also gives good spatial resolution. Slit widths of 10 μ and 25 μ have been used according to the light level available.

Curves of polychromator response as a function of wavelength are given in Fig. 2. Such curves are useful in determining the wavelength separation of the channels. They were obtained by rotating the grating so as to scan the image of a narrow spectral line (H_β) across the light pipes. The outputs of all photomultipliers were connected together and the total signal fed into a recorder. Each peak corresponds to a different channel, the different amplitudes being due primarily to differences in the photomultiplier sensitivities. The resolution of each channel is about 0.5 Å, much less than the half-width of any spectral lines studied (typically 3 to 5 Å.) When the 10-μ slit is used, the resolution is determined primarily by the light-pipe width, hence one does not see a large difference between the response curves with 10-μ and 25-μ slits.

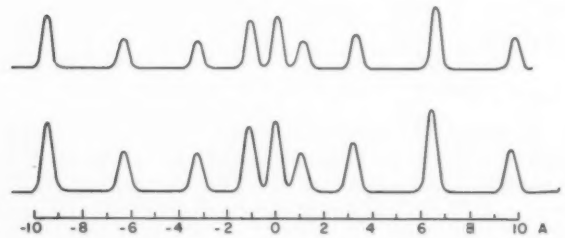

Fig. 2. Polychromator response vs wavelength. The upper curve was made with a 10-μ entrance slit; the lower curve was made with a 25-μ entrance slit. Each peak corresponds to a different channel. The relative spacing of the peaks is determined by the spacing of the light pipes; the outermost channels here are separated by 19.4 Å.

Improvements

The polychromator is presently being modified to increase its sensitivity and versatility. The modifications include an increase in the number of channels from nine to eighteen, the use of straight, rather than tapered, light pipes, and the incorporation of a second cylindrical lens.

A long-focal-length thin cylindrical lens, oriented with its axis perpendicular to the axis of the original (dispersing) lens, is being added to provide focusing of the image in the vertical dimension, with unit magnification. Use of this lens with the tapered light pipes affords about 100% increase in sensitivity by concentrating the light near the vertical center of the light pipes (the transmission of the tapered light pipes is low for light incident on the front of the light pipes near the upper or lower edges). Even larger gains are to be expected in the modified instrument, as the small vertical dimension of the image (about 12.5 mm) will allow the use of straight, rather than tapered, light pipes. Furthermore, the formation of a true (but curved) image at the light-pipe holder permits masks to be placed over the ends of the light pipes, with apertures shaped to conform to the curvature of the image, thus permitting use of a larger portion of the entrance slit without loss of resolution. The new light pipes are also wider and very closely spaced, permitting continuous wavelength coverage over the range of the spectrum covered by the instrument by removal of the masks.

Provisions are being made to cool the photomultipliers to reduce the dark current.

We wish to thank William R. Baker, Wulf B. Kunkel, Forrest I. Boley, Alan DeSilva, and John M. Stone for their helpful discussions and advice. We are also indebted to John Meneghetti and his staff for their able assistance in constructing the instrument. Many details of mechanical design of the modifications which are discussed in the last section are due to Leonard F. Deckard.

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Cloud Chamber for Optical Measurements of Aerosols

Edward Speyer

A cloud chamber is described in which various optical measurements of meteorological interest can be made. A refrigerated chamber of 4 cubic meters has been built, containing a mirror system permitting a range of optical path lengths up to 56 meters. The design of the optical system is explained, together with construction details of the chamber and a description of the two radiation detector systems. The usefulness of the chamber for transmissivity vs distance measurements and for scattering vs transmissivity measurements is indicated by examples of results obtained. Such measurements also can be used to calculate aerosol absorptivities.

Measurements of optical scattering, transmission, and absorption in natural clouds (and fogs) are extremely difficult to reproduce because of the variations between one cloud and another, and in the same cloud with time and position. In the laboratory, clouds (or other aerosols) can be generated and maintained under controlled conditions, and reproduced at will. A cloud chamber for optical meteorological research has been built, chiefly to measure the increases in solar absorptivity resulting from the spray injection of dyes into clouds.[1]

The chamber is a sheet metal (galvanized iron) cylinder 148 cm high and 185 cm in diameter (see Fig. 1), insulated, and maintained between 8°C and 11°C by refrigeration. If a cloud of only low turbidity is needed, one or more spray nozzles can be used for generating the cloud. Here, "turbidity" is used as a catchall term which includes the attenuation due to the number of droplets per unit volume, to droplet size distribution, and to dyes in the droplets. The reciprocal of turbidity can be taken as the distance through the cloud for which the flux reaching the detector is $1/e$ (37%) of the flux reaching the detector when no cloud is present. For such a measurement to be useful, the combined spectral curve of the flux and detector must be specified, and also the angular field of the beam and of the detector. If, as in Fig. 10 and Eq. (4) the beam attenuates exponentially with distance within the cloud, the reciprocal of turbidity becomes identical with the mean free path of a light ray.[2]

Clouds of high turbidity are obtained by injecting steam into the chamber. To avoid warming the chamber, the steam is generated outside the chamber in a pressure vessel (made from an ordinary 4-quart, or 3.8-liter, pressure cooker) fitted with a needle valve control and a pressure gauge. To keep the pressure in the vessel steady, and to minimize the heat needed (a 2000-watt heater is used) the sides of the vessel are wrapped with insulation. Much higher turbidities can be maintained in the cloud chamber than are encountered in natural clouds. It may be remarked, for example, that when an airplane is flying deep inside a cloud, so that a passenger cannot discern by eye whether the sun is above, below, right, or left (isotropic luminous flux), the wingtips of the airplane, perhaps 13 meters from the passenger, are usually as clearly visible, except for occasional wisps of fog, as when the plane is flying in clear air. The likelihood of this can be seen from Fig. 2, which is calculated from the well-known relation

$$P = \frac{1}{\sigma N \pi r^2}, \qquad (1)$$

where

P = mean free path of a light ray,
σ = scattering cross-section coefficient[3] (taken as 2.0 in Fig. 2),
N = average number of droplets per unit volume,
r = droplet radius, assumed constant throughout the cloud (monodisperse aerosol).

The Optical System

From the optical standpoint, the cloud chamber is a long path-length absorption cell, such as is used with infrared spectrometers. A schematic of the projector

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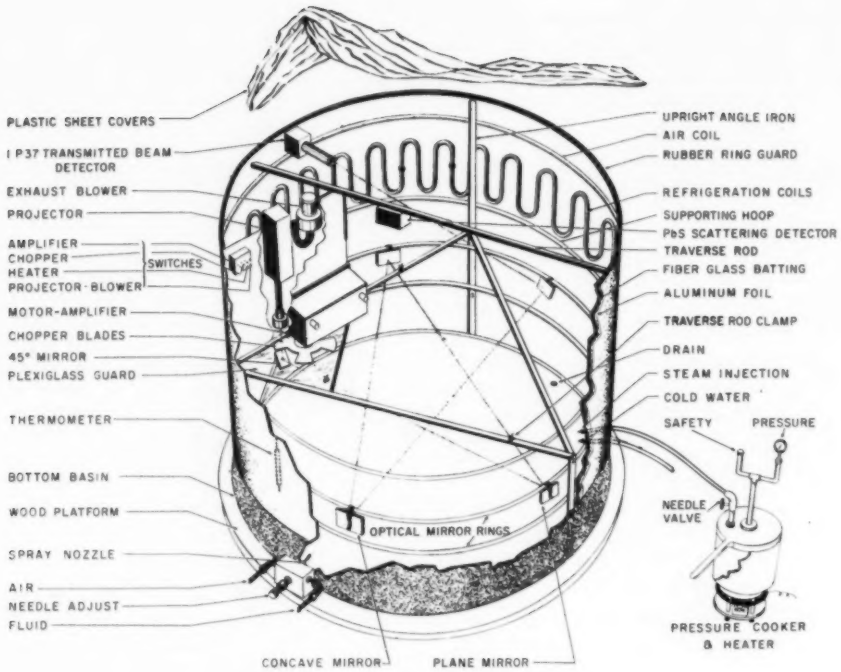

Fig. 1. Cutaway view of cloud chamber.

is shown in Fig. 3, and the folded light path in Fig. 4. The light source is a 300-watt tungsten filament projection lamp operated from a dc power supply and cooled by a small fan, with the exhaust tube leading out

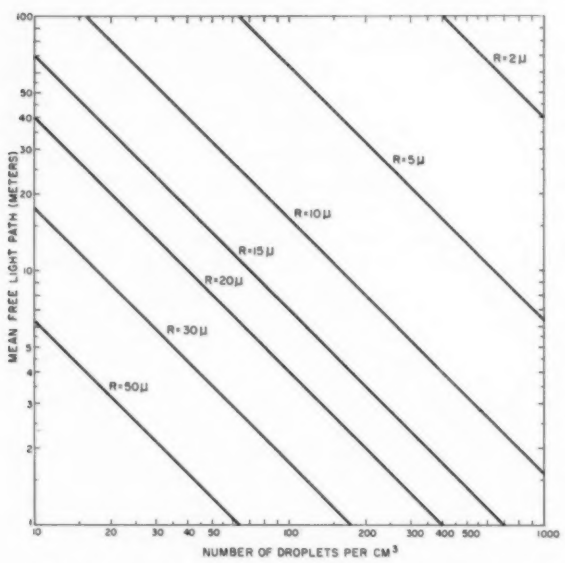

Fig. 2. Mean free path of a light ray in an aerosol as a function of the number of droplets per cm³. Each diagonal line represents the calculated relation for a monodisperse aerosol, with droplet radius given in microns.

of the chamber so as to minimize turbulence. The condenser lenses, two identical achromats, of 60-mm focal length and 19-mm clear aperture, focus the filaments onto a small, adjustable iris diaphragm, called the source diaphragm.

Between the condenser lenses and the source diaphragm there is a compound filter, which converts the tungsten light into approximately the spectral distribution of sunlight. The filter consists of two all-glass liquid cells, having for their common wall a piece of Schott KG-1 filter glass. The two solutions are prepared according to the recipes given in the monograph[4] by Davis and Gibson, recommended by Elliott *et al.*[5]

The objective is an achromat of 37.5 cm focal length and 3.8 cm maximum usable clear aperture. An adjustable iris diaphragm, called the objective diaphragm, is mounted next to the lens. The mounting tube projects about 2 cm beyond the objective lens and is swathed with a strip heater to keep the lens from fogging. The inside of the lens barrel is painted black, but bothersome reflections remain in the beam unless eliminated by baffles. To get adequate beam intensity, the source aperture must be larger than the usual pinhole; however, this necessitates that, in order to keep the beam diameter (and mirrors) small, the source aperture be imaged midway in every third traverse of the beam (see Fig. 4) across the circle to which the mirrors are tangent. This mirror circle is 162.9 cm in diameter, and the traverses, which are chords of this

circle, are either 154.9 cm or 131.8 cm long. The source diaphragm, with its aperture diameter between 0.15 cm and 0.3 cm (depending on the path length being used and signal level required), is 44.5 cm from the objective, making the system with the objective diaphragm wide open about $f/12$. The first image of the source diaphragm is 232.4 cm from the objective, i.e., a 5 × magnified image is formed midway in the second traverse. The divergent beam remains contained because every third mirror (concave) is 14 cm × 11.2 cm instead of the 9 cm × 5 cm aperture of the plane mirrors.

The imaging and re-imaging system resembles those described by White,[6] Howard *et al.*,[7] and Edwards[8] except that it is spread out around a circle which makes it easier to adjust. The two-dimensional spread is desirable in order to make the beam traverse different portions of the cloud. If the beam retraces its own path too closely, the volume of cloud illuminated may represent a poor statistical sample of the cloud as a whole, especially if it is a cloud of low turbidity.

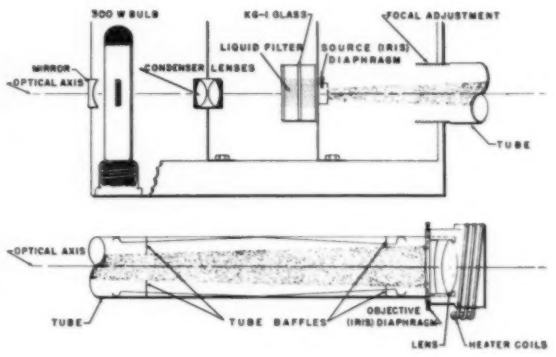

Fig. 3. The optical projector.

The beam diameter is adjusted by the source diaphragm (which controls the size of the images) and by the objective diaphragm (which controls the beam size on the mirrors). The beam must not be allowed to spill over the edges of the mirrors, because not only would light be scattered independently of the aerosol, but the amount scattered would not readily be reproducible.

The mirrors are front-surfaced aluminized, with a protective coating of silicon monoxide. They are prevented from fogging because they are heated by a current of from $1^1/_4$ to 2 amp passed through a coating of 8–10 ohms per square on the back of each mirror. Two horizontal stripes of silver paint are painted across the conducting coating; the mirror is pressed by springs against a plastic backing. (See Fig. 5.) Between each stripe of silver paint and the plastic backing is mounted a copper (phosphor bronze) strip to provide electrical contact. This arrangement keeps

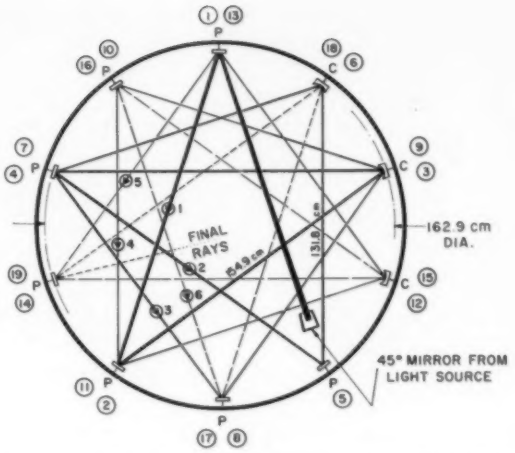

Fig. 4. Diagram of the folded optical path. The images of the source diaphragm are shown as circle-enclosed arrows. P—plane mirror, C—concave mirror.

the mirrors dry only if they do not tilt upward too far from the vertical.

The Concave Mirrors

Ideally, the concave mirrors should be ellipsoids; however, since there are no resolution requirements, spherical mirrors are satisfactory, even though they are used at considerable obliquity. The angle of incidence at the pole of the mirror is 18° for the second, sixth, and seventh images, and 36° for the third, fourth, and fifth. (The first image is formed by the objective.)

The problem is to ensure that the successive images of the source diaphragm are formed at suitable distances along the optical path so that the beam diameter remains smaller than the mirrors. Since the object and image distances for each concave mirror are to be approximately equal, they must be shorter than the

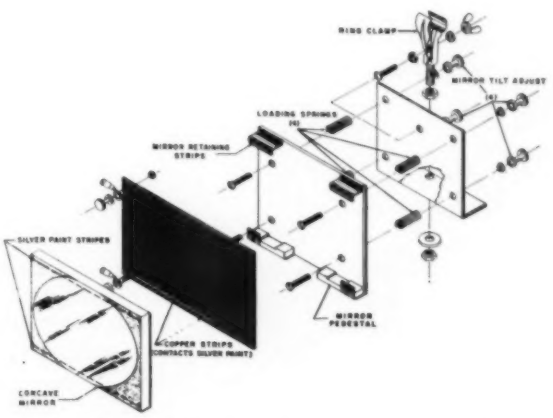

Fig. 5. Exploded view of mirror mount assembly.

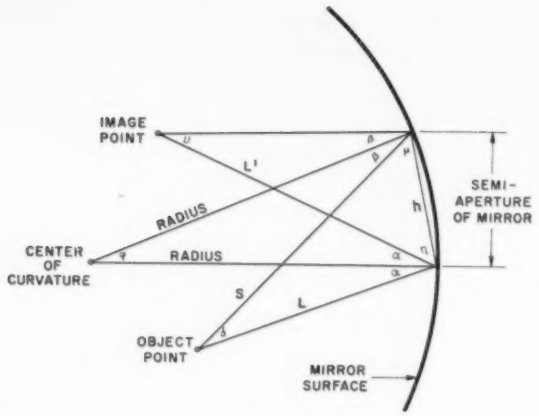

Fig. 6. Ray diagram of the imaging of a point by a concave spherical mirror.

mirror radius. (See Fig. 6.) It is shown in the Appendix that the angle subtended at the center of curvature of a spherical mirror by the chord of its semiaperture is the mean of the two conjugate angles, one of which the chord subtends at the object point, and the other at the image point.

The design procedure followed was to assume a single radius of curvature for the three concave mirrors, and then trace marginal rays through the system. The results are shown in Fig. 7. The asymmetry about the optimum (a mirror radius of 245 cm, not shown) is due to the fact that if the radius is too *long*, the displacement of successive images snowballs (the image can be formed at infinity, or become virtual), whereas if the radius is too *short*, the successive image distances always remain larger than one-half the mirror radius.

The ray trace is facilitated by using the equations:

$$S = \frac{h\left[(h/L)\sin\varphi + \cos\left(\alpha - \frac{3}{2}\varphi\right)\right]}{\sin 2\varphi - (h/L)\cos\left(\alpha + \frac{3}{2}\varphi\right)} \tag{2}$$

$$L' = \frac{h\left[(h/L)\sin\varphi + \cos\left(\alpha + \frac{3}{2}\varphi\right)\right]}{\sin 2\varphi - (h/L)\cos\left(\alpha - \frac{3}{2}\varphi\right)} \tag{3}$$

where

$$\varphi = 2 \arcsin h/2R.$$

R and α are known; and h and L are known for the first spherical mirror.

The oblique spherical aberration is readily calculated from these equations, as is the increased aperture which must be provided by the mirrors to intercept the entire beam. The derivation is given in the Appendix. The curvature of field can be estimated from the monotonic, and nonlinear, shortening of the image distance with increasing angle of obliquity.

Figure 7 shows that there is little to be gained by using a different radius for each of the three concave mirrors. Moreover, the position of the successive images is not completely determined by the radius chosen because a small adjustment can be made by raising or lowering the projector and/or the objective lens, i.e., the position of the first image (zero line in Fig. 7) can be displaced.

Although it was not done in the present experiments, the optical path length can be doubled by placing a plane mirror at the seventh image and sending the light back along its own path.

The Detector Systems

Since 98% of the solar energy reaching lower altitudes has wavelengths between 0.3 μ and 2.5 μ, a lead sulfide detector is used. It is a 1-cm-square Ektron detector, type "Q" (suitable for use in humid atmospheres). The dark resistance is 950,000 ohms. A 1.3-megohm low-noise resistor is matched to the detector and a 90-volt low-noise battery bias is maintained across the detector and the load (see Fig. 8). The minimum detectable signal (for 1 cps bandwidth) is given by the manufacturer as less than 4×10^{-11} watts/cm^2 between 1 μ and 2.6 μ. The sensitivity is at least half as great throughout the visible and near ultraviolet.[9]

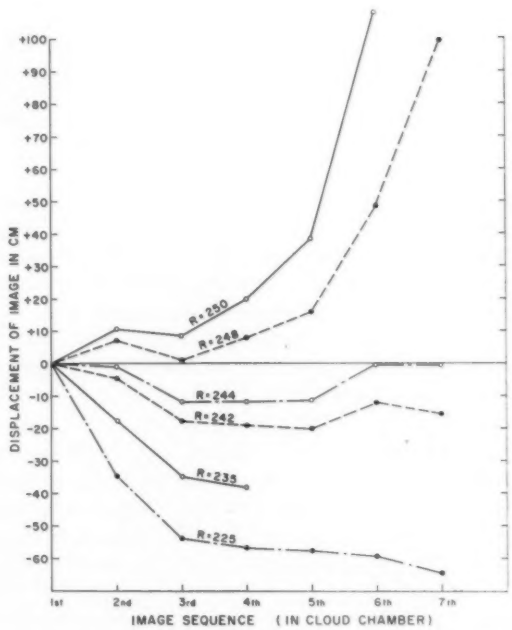

Fig. 7. Successive image displacements, measured from the traverse midpoints, using concave spherical mirrors of radius R, in centimeters. The approximate nominal image positions are shown as circle-enclosed arrows in Fig. 4.

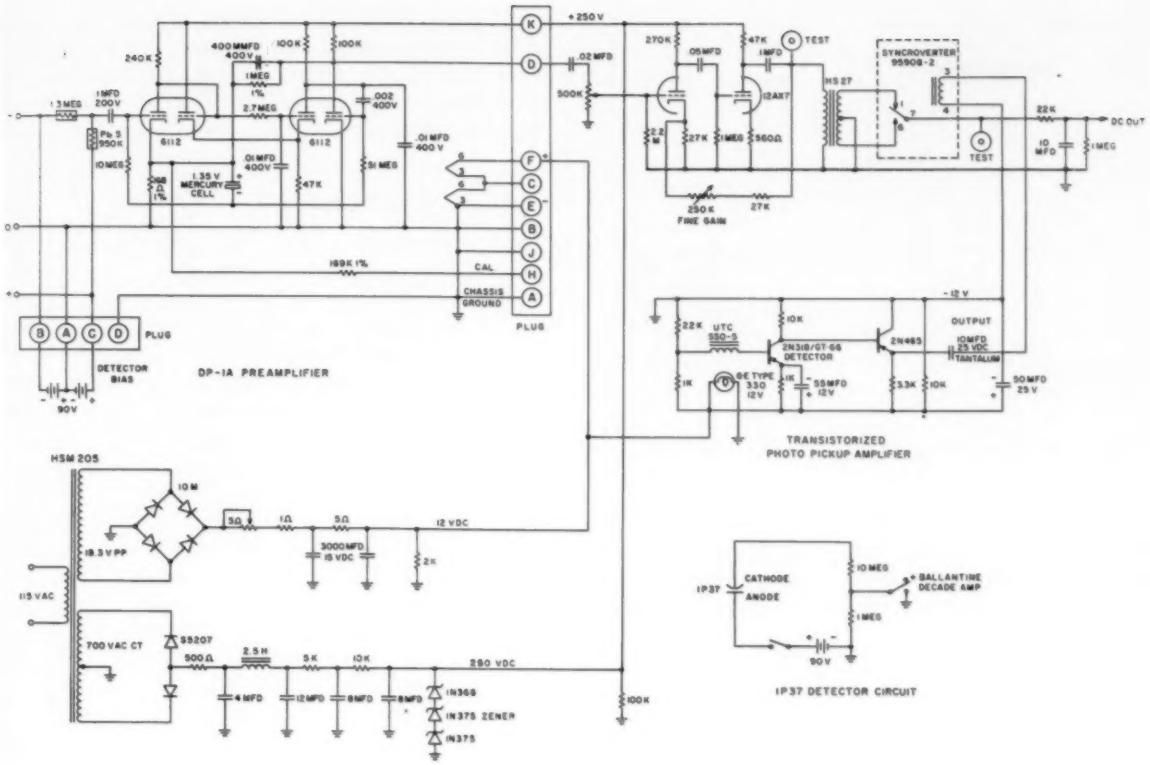

Fig. 8. Detector system wiring diagram.

The preamplifier (Barnes Engineering Model DP-1A) is a four stage unit utilizing two dual-triodes. The high gain (5000, or 74 dB) and low output impedance (1500 ohms) make it possible to connect the unit to following stages with low noise pickup. The internal noise is less than 1.2 μV rms between 6 cps and 500 cps. Stabilization is achieved by both feedback and calibration signals, which are applied to the cathode circuit of the input stage (see Fig. 8). A 1.35-volt mercury cell is used for biasing the first and last stages. To minimize noise pickup, the leads from the lead sulfide to the preamp are only 1.8 cm long.

The signal is normally chopped in infrared detection systems to reduce drift by permitting the use of ac, instead of dc, amplification. If the amplifier is sharply tuned to the chopping frequency, it will eliminate the noise at all other frequencies. However, this means that the system will be sensitive to any change in chopping frequency; if the chopping blade rotates a little faster or slower than normal, the signal output will be reduced. To retain the noise suppression achieved by sharp tuning, and yet free the system from sensitivity to chopping frequency, the chopped signal is rectified by a syncroverter which is actuated by a synchronizing pulse from a phototransistor reference pickup. The rectified output signal is then filtered so as to pass only information between dc and 1 cps.

The preamp output is coupled through a dc blocking condenser to the input of the syncroverter amplifier circuit, which is limited to a maximum output of 10 volts, 2 mA. This amplifier serves as an isolating stage with a gain of unity. The syncroverter (Bristol Co., Model 95908-2) serves as a mechanical full-wave dc rectifier.

The phototransistor reference pickup (Barnes Engineering, Model PRP-2A) uses a GE type 330 lamp as a source and a GT-66 phototransistor as a detector. A small chopper blade, mounted on the same shaft as the main beam chopper (see Fig. 9), rotates between the lamp and the phototransistor, whence is generated the signal actuating the syncroverter. Phase adjustment of the synchronizing signal is achieved by manually rotating the photo pickup unit through a small angle about the chopper shaft; the adjustment is monitored by superimposing the preamp signal output and the phototransistor signal output on a dual-beam oscilloscope. The rectified signal from the syncroverter output is filtered and directly coupled to a recorder or meter.

A 12-volt dc bridge supply serves four functions:

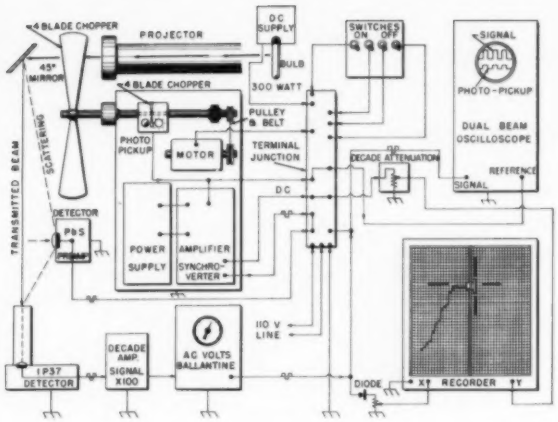

Fig. 9. Schematic block diagram of the detector systems.

(1) it heats the two triode filaments in the preamp; (2) it heats the triode filament in the syncroverter amplifier; (3) it lights the lamp in the photo pickup; (4) it provides the dc bias voltage for the phototransistor amplifier.

The B+ voltage (250 volts) for the preamp and for the syncroverter amplifier is taken from a full-wave rectifier through a four-section filter, and regulated by three Zener diodes. The ripple in the B+ voltage is 0.004% and the regulation between load and no-load is 0.4%. Both dc power supplies, together with the syncroverter amplifier, the photo pickup, and the chopper motor and pulley, are mounted in a sealed housing (see Fig. 1, "motor-amplifier").

The common return for the zero volt reference in the preamp is grounded to the sealed housing as are the outside shields of the filament, B+, and signal. In addition, the sealed housing and the chamber structure (including the aluminum foil on the outside of the fiber glass batting) are connected to earth ground to reduce stray radiation and noisy ground loops.

If the detector does not need to be sensitive over the entire range 0.3 μ to 2.5 μ, a phototube can be used instead of PbS. If there is plenty of signal, as in most transmitted beams, the simplified system shown in the lower right-hand corner of Fig. 8 can be used. The 1P37 phototube is battery biased with 90 volts, divided between a 10-MΩ load resistor and a 1-MΩ signal output resistor. The tube is shock-mounted in a sealed housing. The 1P37 output is amplified by a Ballantine Decade Amplifier (Model 220C) and a Ballantine ac voltmeter (Model 300) used as an amplifier. The amplified signal is series rectified through a diode, filtered and connected directly to a recorder or meter.

The noise level of the detector systems is checked, and system difficulties traced, with the aid of an artificial constant "cloud." A piece of ground glass is inserted part-way into the beam; the voltage on the 300-watt lamp is then slowly varied, and the readouts checked for reproducibility. In the present setup, the mean deviation is about 2% of the full deflection for both detectors.

Structure of the Chamber

The bottom basin, with a wall 36 cm high, is watertight, and resembles a child's wading pool. Rigidity for the main chamber wall is provided by three upright angle irons to which are welded three horizontal supporting hoops (only the middle hoop is shown in Fig. 1); the bottom hoop also is welded to the inside of the basin wall. The main chamber wall is a separate strip draped around the two upper hoops, with the ends of the strip clamped together. The chamber is thus easy to disassemble for transport. The lower edge of the wall rests on the bottom hoop, i.e., inside the basin wall. The chamber roof consists only of two large plastic sheets, used one on top of the other, with the edges hanging down the outside. Sagging of the plastic sheets in the center of the chamber is prevented by two cross-rods (not shown in Fig. 1) clamped to the rim of the wall. When no cloud is being generated, the plastic sheets are thrown back. When it is desired to enter the chamber, a stepladder is put inside the chamber, so that a man standing on a stool can step over the top of the wall.

The walls and floor of the cloud chamber are painted with aluminum paint, as a crude simulation of a cloud background. For effective rust prevention, an undercoat of fish oil paint was first applied. The steam is injected into the chamber via a $^1/_4$-in. (6-mm) copper tube, through a hole 13 cm above the chamber floor.

Serpentined around the inside of the chamber wall is 28 meters of $^1/_2$-in. (12-mm) copper cooling coil. The coil is attached directly to the wall, which thus acts somewhat as a giant fin. The mounting brackets permit the entire coil to be raised or lowered. The compressor, a one-ton (200 Btu/min, or 3.5 kW of cooling) heavy-duty air-conditioning unit, is mounted on the laboratory floor outside the chamber.

A copper air coil, with small holes punctured in the bottom, is mounted above the cooling coils. Three to four atmospheres pressure in the air coil causes a cold air current to blow down over the cooling coils, which (1) assists the compressor in rapidly cooling the chamber, (2) assists in completing the dissipation of clouds, and (3) de-ices the coils.

Colder and more lamellar temperatures were obtained by hanging additional cooling coils in the middle of the chamber. This finned unit, which was approximately a cube 40 cm on an edge, greatly reduced the tendency of the wall coils to ice up, thus causing the compressor to transport more heat out of the chamber.

With this unit in place, however, the chamber became inconveniently difficult to enter or to work in, so the unit was discarded.

Generation, Maintenance, and Dyeing of Clouds

About 25 min before a cloud is wanted:

1. Cold water is run into the chamber until the bottom is covered.
2. Ice cubes are put in the water.
3. The compressor is turned on, but cycled to prevent icing of the coils.
4. Air at 3–4 atm pressure is run through the air coil.
5. The pressure cooker is half-filled with water, and the heater under it is turned on.
6. The plastic covers are spread over the top of the chamber.

When the chamber temperature drops below 10°C and the pressure cooker gauge shows 3.7 atm, the air coil pressure is turned off and steam is injected into the chamber until the desired turbidity is obtained.

With the first arrangement tried, a pressure cooker was not used; the clouds were generated by heating the water (with an immersion heater) on the floor of the chamber. The upper third of the chamber was refrigerated, and the lower third was warmed by the steaming water. The middle third was left uninsulated, that is, the laboratory was used as "thermal ground" to hold the middle portion of the chamber at room temperature. It was hoped that the cloud might settle and hang quietly. The mirror circle together with the projector are designed to be raised and lowered as a unit within the cloud, so that the transmission could be compared for different droplet size distributions (i.e., levels) within the cloud.

However, turbulence rendered vertical scanning meaningless. Additional difficulties were caused by the large thermal inertia of the water on the floor, which made turbidity adjustment too slow and inaccurate. Although extremely turbid clouds were generated when hot water was run into the cold chamber, the large water surface gave off so much heat that the refrigeration unit was overpowered, and could not maintain the upper third of the chamber sufficiently below room temperature.

The present arrangement permits the maintenance of clouds over a large range of turbidity. Clouds which attenuate 99% of the incident beam in less than 1 meter have been maintained. In a few cases, turbidities were so high that the scattering began to *decrease* as the turbidity was increased. This signified that the mean free path of the light rays had become shorter than the distance of the detector (40 cm) above the mirror circle. In such cases, the scattering signal went through a maximum as the cloud was allowed to dissipate.

It is more difficult to maintain a steady transmitted beam than a steady scattering level because the latter represents an integral over a much larger solid angle of detector field of view. The scattering signal can be kept constant within plus or minus 5% over periods of 20 min and longer by varying the rate of steam injection, with the needle valve shown in Fig. 1. Further stability improvement could be obtained through a feedback system, using a monitoring detector to regulate the steam injection rate.

When wanted, dye solution is sprayed into a cloud with a $^1/_4$ JN type nozzle. The nozzle is mounted below the mirror circle (see Fig. 1) so that large droplets will fall into the water at the bottom with minimum effect on the detector readings. The spray is directed slightly upward to aid the mixing of the spray droplets in the cloud.

Applications

1. The PbS detector was mounted so that it could be moved along the light beam in either the first or second traverse,* and the transmissivity data shown in Fig. 10 were taken. The detector was moved by hand, and readings taken every 10 cm. The positions were repeated in different sequence, to ensure that the turbidity was not varying significantly with time. The readings were divided by those taken at the same positions when no cloud was in the chamber.

For these measurements, the detector is fitted with a projecting tube along which can be moved a metal disk with a small hole in its center. The angular field of view of the detector is thus not only restricted,[10] but can be varied in a simple way, so that extrapolation can be made to zero field angle, i.e., to the case where only directly transmitted light, with no singly scattered light, reaches the sensitive surface. The extrapolation is not usually necessary, however, since the coefficient of scattering cross section for the droplets lies between 1.9 and 2.0 for any cone-angle[2] less than 5°.

The data, of which Fig. 10 is an example, indicate that for narrow field angles an exponential of the form

$$I = I_0 e^{-x/\delta} \tag{4}$$

fits within the limits of experimental error. The constant δ represents the distance at which the beam is attenuated to 37% of its original intensity.[2]

2. If the aerosol has significant absorption, cloud chamber measurements may provide an indication of the mean free path of a photon before it is absorbed. We cannot simply expand the exponent in Eq. (4) to $-x[(1/\delta_s + 1/\delta_a)]$, where the subscripts refer to scattering and absorption, because most of the ab-

* With multiply folded paths, consideration must be given to light which "short-circuits," i.e., is scattered at a beam intersection and goes down the "wrong" beam.

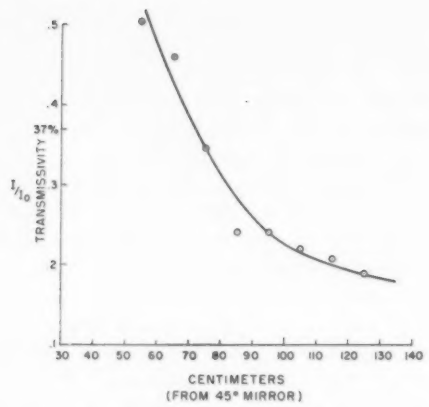

Fig. 10. Transmissivity vs distance in aerosol, measured with a narrow-angle detector.

sorbed photons are those which have been scattered out of the direct beam. Therefore, we must measure the attenuation of the scattered light, which means we must use a wide-angle (actually, a hemispherical) detector. The problem is similar to that encountered in analyzing by means of x rays or neutrons the scattering and absorption in a slab.* (Neutron absorption can sometimes be distinguished from neutron scattering by gamma-ray emission; analogous optical techniques using fluorescent dyes might be useful.)

If transmissivity measurements are made with the field of view of the detector unrestricted, the data might be fitted by an empirical function:

$$I = f(I_0, \mathrm{x}, \delta_a{}^*, \delta_a{}^*), \qquad (5)$$

where the asterisk indicates that a wide field of view is being used.

Even though the scattering function, and certainly $\delta_a{}^*$, can be expected to vary with wavelength, it should not be necessary to include the wavelength as a variable in Eq. (5), i.e., to use various monochromatic light beams. The mean free path for absorption can be ascertained as an average over a wide spectral range, including several absorption bands, if some of the transmissivity measurements are made with light restricted to spectral regions which definitely do *not* include any significant absorption bands. The latter measurements can be substituted into Eq. (5), with an infinite value for $\delta_a{}^*$. In order, however, that the scattering function shall remain reasonably unchanged (between light with, and without, absorption bands), the center of gravity of the combined light source–filter–detector spectral curves should remain substantially fixed. If corrections are made for goniophotometric reflection losses at the detector surface and for scattering by the chamber walls, it may be possible to calculate $\delta_a{}^*$.

3. Another type of result obtained with the cloud chamber is shown by Fig. 11. An 8.05-meter path length was used. The detector arrangement is shown in Figs. 1 and 9. The *X-Y* recording (Fig. 11) shows scattered flux in arbitrary units versus percent transmission. The overlapping curves show the degree of reproducibility obtained with clean clouds; the lower curve was obtained when a dye solution was sprayed into the cloud. The distance between the curves was used to calculate the percentage increase in solar energy absorptivity. This increase is shown by the straight line, with the scale at the right. These measurements were made as part of an investigation of the feasibility of dissipating clouds and fog (weather modification) by increasing the amount of solar energy absorbed. This work is reported elsewhere.[1]

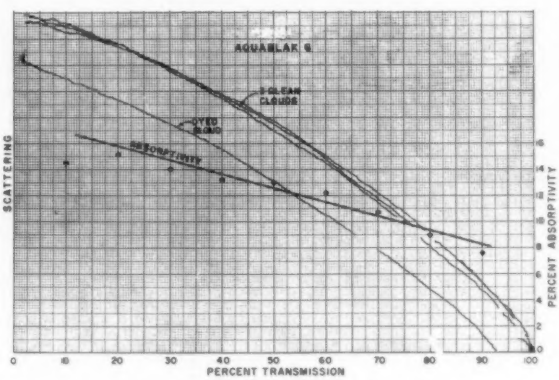

Fig. 11. Scattered energy (arbitrary units) vs percent transmitted, recorded for several clean clouds and one dye-sprayed cloud. The straight line is the calculated increase in solar absorptivity, with percentage scale shown at right.

We are indebted to many people for encouragement and assistance; the most important contributions are listed in ref. 1. Here there is space only to mention our assistant, Martin Miller, who built the cloud chamber and most of the equipment used in it.

Appendix

Figure 6 shows two rays reflected at the spherical mirror surface, a paraxial ray and a marginal ray. The two angles of reflection are α and β.

(a) *The angle φ subtended by the semiaperture chord h at the center of curvature equals $(\delta + \nu)/2$, the average of the conjugate angles subtending h.*

We consider three triangles having h for a base and apex angles φ, δ, or ν. The isosceles triangle with apex φ can be divided into two right triangles by bisecting φ; the three angles of the other two triangles are then seen to be

* Note added in proof: Wootten [Brit. J. Appl. Phys. **13**, 406 (1962)] places the light source in the center of a spherical cloud, instead of outside the cloud-slab as occurs with the sun. His measurements give graphs from which, by formulas which unfortunately are not derived in the paper, he is able to read off both the absorptivity and the fraction of light scattered.

$$\delta + \left(90° - \frac{\varphi}{2} + \alpha\right) + \left(90° - \frac{\varphi}{2} - \beta\right) = 180°, \quad (6)$$

$$\nu + \left(90° - \frac{\varphi}{2} - \alpha\right) + \left(90° - \frac{\varphi}{2} + \beta\right) = 180°, \quad (7)$$

whence, by simplifying and adding (6) and (7),

$$\varphi = \frac{\delta + \nu}{2}. \quad (8)$$

(b) *Derivation of*

$$S = \frac{h\left[(h/L)\sin\varphi + \cos\left(\alpha - \frac{3}{2}\varphi\right)\right]}{\sin 2\varphi - (h/L)\cos\left(\alpha + \frac{3}{2}\varphi\right)}. \quad (2)$$

From the law of sines we have

$$\frac{S}{\sin(2\alpha + \eta)} = \frac{h}{\sin\delta} = \frac{L}{\sin\mu}. \quad (9)$$

From the isosceles triangle with apex angle φ, we have

$$\varphi + 2(\alpha + \eta) = 180° = \varphi + 2(\beta + \mu). \quad (10)$$

Substituting Eqs. (6) and (10) into Eq. (9),

$$S = h\frac{\sin\left(90 - \frac{1}{2}\varphi + \alpha\right)}{\sin(\varphi - \alpha + \beta)} = h\frac{\cos\left(\alpha - \frac{1}{2}\varphi\right)}{\sin(\varphi - \alpha + \beta)} \quad (11)$$

Expanding both numerator and denominator and dividing by $\cos\beta$, we get

$$S = h\frac{\cos\frac{1}{2}\varphi - \sin\frac{1}{2}\varphi\tan\beta}{\sin(\varphi + \alpha) - \cos(\varphi + \alpha)\tan\beta}. \quad (12)$$

Using the second parts of Eqs. (9) and (10) we find

$$\tan\beta = \frac{(h/L)\cos\frac{1}{2}\varphi - \sin(\varphi - \alpha)}{(h/L)\sin\frac{1}{2}\varphi + \cos(\varphi - \alpha)} \quad (13)$$

Substituting Eq. (13) into Eq. (12), expanding, and taking advantage of the fact that the cosine is an even function, we get Eq. (2).

(c) The derivation of Eq. (3) follows the same logical sequence as the derivation of Eq. (2), with Eq. (7) being used instead of Eq. (6).

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CORPORATION MEMBERS OF THE OPTICAL SOCIETY OF AMERICA

AEROJET-GENERAL CORPORATION, Azusa, California, *carries on optical research and development at the Astronics Division. Approximately 850 engineering and supporting personnel are engaged in the various aspects of research and development of infrared and optical instrumentation for scientific and military applications. Prime fields of interest are surveillance, tracking, fire control, and measurements in airborne and space environments. Facilities are provided for design, fabrication, laboratory studies, and manufacturing.*

AERONUTRONIC DIVISION, FORD MOTOR COMPANY, Newport Beach, California, *is geared to help meet the defense and related commercial needs of the United States. Aeronutronic is a part of Ford's Defense Products Group, which also consists of the Special Military Vehicles Operations in Dearborn, Michigan. The Newport Beach firm is engaged in development and manufacture of tactical weapons, space systems, strategic systems, and electronics.*

AEROSPACE CORPORATION, El Segundo, California, *is a nonprofit public service institution and does not engage in production or manufacture of hardware. It was formed in June 1960 to provide an organization of high technical competence to assist the Air Force in the scientific-engineering planning and direction of missile-space programs. The Corporation engages in forward planning in connection with advanced ballistic missile and space systems.*

AMERICAN ASTROPHYSICS, 2000 South Myrtle Avenue, Monrovia, California, *is equipped to service government and industry in research, development, and production in the fields of optics, space technology, astrophysics, aeronautical sciences, electronics, and applied mechanics. The firm is currently engaged in the research, study, design, and fabrication of an electro-optical surveillance station to be used for visually determining the characteristics of orbiting satellites. Other areas of activities include research in electronics and optics for such equipments as advanced telescopes, cinetheodolites, infrared thermal detection and ranging systems, and television systems for imaging and display.*

AMERICAN CYSTOSCOPE MAKERS, INC., Pelham Manor, New York, *has been engaged in the design, development, and manufacture of optical and electronic, diagnostic and operative medical equipment since 1906. It has been engaged in the development of fiber optics for the past twelve years and has been active in the manufacture of fire control systems, telescopes, periscopes, range finders, bombsights, and other military and industrial inspection equipment such as borescopes and alignment telescopes.*

AMERICAN OPTICAL COMPANY, Southbridge, Massachusetts, *founded in 1833, manufactures ophthalmic products. More than 2000 different products are made, ranging from the tiny screws used in fashionable eyewear to space helmets and missile trackers. It also manufactures safety products, sun glasses, and scientific instruments, including microscopes and telescopes. The research center is devoted to the application of basic science to improving man's perception of his environment.*

ANSCO DIVISION, GENERAL ANILINE AND FILM CORPORATION, Binghamton, New York.

APPLIED PHYSICS CORPORATION, 2724 South Peck Road, Monrovia, Calif., *founded in 1946, produced the first commercial UV-visible range recording spectrophotometer. Present products include ultraviolet-visible-near-IR, infrared, and Raman recording spectrophotometers; vibrating reed electrometers for precise measurement of extremely small charges, current, and voltage in pH, radioactivity, electronic, mass spectrophotometry, space exploration, and other applications; chromatography-radioactivity analysis systems.*

BAIRD-ATOMIC, INC., 33 University Road, Cambridge, Massachusetts, *was founded for consulting and instrument development in the area of applied physics. Incorporated as Baird-Associates in 1947, the Cambridge, Massachusetts, firm merged with the Atomic Instrument Company in 1956. Today, Baird-Atomic, Inc., derives its business from commercial sales of atomic, spectrochemical, and electronic instruments in addition to research, development, and engineering contracts for various U.S. government agencies.*

BARNES ENGINEERING COMPANY, Stamford, Connecticut, *is engaged in the fields of infrared and electro-optics, in which its activities include research, design, development, and manufacture of components, instruments, and systems. It specializes in the production of infrared detectors, radiation sources, instruments for the measurement and analysis of infrared radiation, and thermal scanning cameras. The Company has pioneered in the development of missile and space vehicle instrumentation including trackers, horizon sensors, and meteorological radiometers; Barnes equipment is currently being employed in such important programs as Polaris, Tiros, Nimbus, and Project Mercury.*

BAUSCH & LOMB INC., Rochester 2, New York, *founded in 1853, is a manufacturer of ophthalmic products and scientific instruments. Eyewear and related diagnostic and prescription equipment account for roughly half of the sales. The product line also includes a wide range of instruments for analytical, industrial, medical, educational, motion picture, and military use; optical glass, lenses, mirrors, and reflectors. In addition, research and development programs are underway in several areas of electronics and radiation measurements, and basic studies are carried out on the effects of radiation on glass.*

BECKMAN INSTRUMENTS, INC., 2500 Fullerton Road, Fullerton, California, *manufactures electronic instruments, systems, and components for analysis, measurement, and control. Founded in 1935 with the first commercial pH meter, the Company soon introduced its first precision optical instrument, the spectrophotometer. Today more than 400 Beckman products serve throughout the world in scientific, industrial, medical, and space applications; and in addition to manufacturing facilities in Fullerton, Germany, and Scotland, the Company has sales and service representatives in most of the key cities of the United States and in 50 foreign countries.*

BELL AND HOWELL COMPANY, Chicago, Illinois

BELL TELEPHONE LABORATORIES, INC., New York, New York, *research and development unit of the Bell System. Its basic function is advancing the technology behind Bell System communications. The activity is broad, ranging from fundamental research (which created the transistor) to the engineering of complete systems (such as the transcontinental microwave system). Activities for national defense are exemplified by the development of the Nike-Hercules System, and the Command Guidance System used for the Titan missile and satellite orbiting vehicles.*

BENDIX CORPORATION, Detroit, Michigan, *began in 1929 with an original output of a handful of products, the most important of which were starter drives and four-wheel brakes; today the Corporation develops and produces hundreds of diversified products. In addition to the original automotive component line, the Corporation is a factor in communications, instruments, computers, nucleonics, detection, and missile systems development and manufacture.*

CHICAGO AERIAL INDUSTRIAL, INC., Barrington, Illinois; *its precision optical capability has been enhanced through the acquisition of Pacific Optical Corporation, Inglewood, California. Specialists in precision high acuity lenses for reconnaissance cameras, Pacific Optical provides optical system knowledge to complete CAI's capability in optics, mechanics, and electronics. Utilizing knowledge of sophisticated plastics, Pacific Optical engineers are developing viewing ports for supersonic aircraft and space vehicles. Other work is the development of infrared systems, optical elements for ultra-fast readout of data processing cards, wide-angle cartographic lenses, and group projection systems for ground stations monitoring data transmissions from orbiting space vehicles.*

CORNING GLASS WORKS, Corning, New York, *manufacturer of specialty glasses, was founded in 1851. The basis of company growth has been the development of new materials and new products for use in science, industry, and the home. In 1908 Corning founded a research and development laboratory, and formulas for more than 75,000 different types of glass have been recorded since that time. Process developments have included the mass production of optical glass in 1944 and subsequent manufacture of a wide range of optical and ophthalmic glasses.*

AVIDSON OPTRONICS, INC., 2223 Ramona Boulevard, West Covina, California, *main activity is manufacturing optical and electro-optical instruments for precise angular measurements. The Company pioneered the development of automatic autocollimators and now manufactures a large variety of these instruments. Also active in angular and linear measuring devices, based on precision scales, capable of developing advanced optical and electro-optical readout devices. Produces precision glass circles, scales, and reticles. Optical Department has facilities for grinding and polishing small and large observatory optics, present undertakings being, the Navy's 60-in. (1.52-m) Astrometric Telescope and the Air Force 48-in. (1.22-m) Satellite Observation Telescope. Newest development is optically controlled Hydrodynamic Test Stands for testing gyros and guidance platforms.*

E. I. DUPONT DE NEMOURS AND COMPANY, INC., Flint Laboratory, St. John and Hamilton Streets, Flint, Michigan, *provides technical support for the sale of DuPont paint products to the automotive industry. Specialized skills in the important sciences related to this area of finishes application are concentrated in a professional staff composed principally of physicists, chemists, and engineers. The Laboratory includes a well-equipped facility for measurement, specification, and control of color and other appearance attributes of organic finishes.*

E. I. DUPONT DE NEMOURS AND COMPANY, INC., Photo Products Department, Wilmington 98, Delaware, *manufactures and distributes an entire line of photographic products including x-ray films, screens, and chemicals; motion picture films; graphic arts films and chemicals; engineering reproduction and drafting films; "Cronar" polyester photographic films; photorecording and photocopy films and papers; professional photographic films, papers, and chemicals; and "Dycril" photopolymer printing plates. The Photo Products Department operates five plant and laboratory locations as well as sales offices throughout the United States. Its products are also sold in 73 foreign countries.*

EASTMAN KODAK COMPANY, Rochester, New York, *is a manufacturing concern founded by George Eastman in 1889. It has major plants in Rochester, New York; Kingsport, Tennessee; Longview, Texas; Peabody, Massachusetts; England; France; Canada; Germany; and Australia. Kodak and its subsidiaries manufacture amateur and professional photographic equipment, films, paper and chemicals, optical and mechanical equipment, vitamin concentrates and monoglycerides, man-made fibers, plastics, industrial chemicals, and special equipment for the armed forces.*

EDMUND SCIENTIFIC CORPORATION, Barrington, New Jersey, *is an optical and science mail-order house, supplying optics to research centers, university and industrial laboratories, and educational institutions. Edmund has a stock of war surplus optical parts and items, most adaptable to many present-day uses. Edmund offers telescopes, microscopes, binoculars, and industrial magnifiers and optical measuring devices, including a low-priced American-made stereo microscope. Edmund offers lenses —achromatic, convex, concave, meniscus, etc., prisms of all types—right angle, porro, amici roof, dove rhomboidal, leman, etc., plus many science learning and teaching aids.*

EDNALITE OPTICAL COMPANY, INC., PEEKSKILL, New York, *has three divisions, Industrial Optics; Instrumentation; and Photographic; the major contributions in the optical instrumentation field involve the initial development of filter glasses with highly precise transmissions and absorptions for photography and instrument uses; Zoom systems for photography and television uses; optical measuring systems; and projection and photography devices for commercial and highly technical purposes.*

ELGEET OPTICAL COMPANY, INC., 838 Smith Street, Rochester, New York, *fabricates lens assemblies, optical instruments and systems from the initial design stages through engineering, prototype production, and the ultimate completed unit.*

EPPLEY LABORATORY, INC., 12 Sheffield Avenue, Newport, Rhode Island, *was founded in 1915 for the purpose of manufacturing standard cells, and other products were developed: precision dc measuring instruments, thermopiles of various types, and the Eppley pyrheliometer for the measurement of total solar and sky radiation. After the Second World War interest in thermal detectors continued with the production of the Golay pneumatic infrared detector. Recently, Eppley has enlarged its line of pyrheliometric equipment and also offers certain calibration facilities in the thermal radiation field.*

FAIRCHILD CAMERA AND INSTRUMENT CORPORATION, Syosset, New York, *in the past forty years has developed its capabilities in optics, electronics, and mechanics. Of eleven divisions, four have concentrated in the field of optical engineering: Defense Products Division designs and manufactures optical systems and subsystems for the military and is engaged in basic research. Graphic Equipment Division is a pioneer in optical applications for the graphic arts industry. Du Mont Division provides specialized optical instruments for the military, industry, and commerce. Industrial Products Division produces and distributes cameras and optical instruments.*

FARRAND OPTICAL COMPANY, INC., Bronx Blvd. & E. 238th St., New York 70, N.Y., *is engaged in research, design, production of prototypes, and manufacture in quantity of individual components or complete optical, mechanical, and electronic systems. Farrand pioneered in infrared research and infrared systems development, worked in the far ultraviolet, and is now applying lasers in several fields.*

J. W. FECKER, INC., 4709 Baum Boulevard, Pittsburgh, Pennsylvania, *is the direct descendant of the optical instrument firm founded by John Brashear in Pittsburgh about 1878, and has built many of the principal astronomical instruments in America. The Company makes large telescopes, spectrographs, Schmidt cameras, and electro-mechanical equipment for testing gyroscopes, and also imports photographic theodolites made by Contraves in Switzerland. An important typical product is a photographic telescope with an 18-in. aperture and focal lengths up to 500 in. for photographing missile tests.*

FERSON OPTICS, INC., Ocean Springs, Mississippi, *'s efforts are devoted primarily to the design and production of high precision optical instruments and components, including interferometers, reference flats, plane parallels, complex periscopes, and accessories. Professional observatories, experimental laboratories, colleges, universities, and such government agencies as the Smithsonian Institution and the Bureau of Standards are among many repeat customers. Plant capacity was recently increased some seventy percent and the list of employees is being expanded as rapidly as training requirements will allow.*

FISH-SCHURMAN CORPORATION, 70 Portman Road, New Rochelle, New York; *Schott-Mainz (Western Germany) raw optical glass, including rare earth glasses; interference filters for visible, ultraviolet, and infrared spectral region; solid colored optical glass filters; non-Browning glass; radiation shielding glass; precision-bore glass tubes; low reflective and dichroic coating; Royal Berlin Laboratory porcelain; condensing lenses; Hoeppler precision viscosimeter; Ubbelohde viscosimeter; Zirconarc lamp for photomicrography; color compensating head for printing color film.*

GAERTNER SCIENTIFIC CORPORATION, Chicago, Illinois

GENERAL ELECTRIC COMPANY, LAMP DIVISION, Nela Park, Cleveland 12, Ohio, *is headquarters for 40 plants and some 70 sales and distribution offices as well as 10 engineering and research laboratories, and 6 product departments for large lamps, miniature lamps, photo lamps, lamp glass, lamp metals and components, and outdoor lighting (Hendersonville, N.C.). The Nela Park facility Lighting Research and Development Operation comprises laboratories for lamp research, lamp engineering research, and radiant energy effects. R&D interests of the Division include light sources and their properties, spectra, color and color systems, optical properties of phosphors, etc.*

GENERAL TELEPHONE AND ELECTRONICS LABORATORIES, INC., Bayside, New York, *carry out research programs for the Corporation and its manufacturing activities such as Sylvania Electric Products, New York; Argus Cameras, Ann Arbor, Michigan; Automatic Electric, Chicago; Leich Electric, Genoa, Ill.; Electronic Secretary Industries, Waukesha, Wisconsin, and Lenkurt Electric, San Carlos, California. The product range includes: incandescent, fluorescent, electroluminescent, and photoflash lamps, cameras, projectors, telephone instruments, switchboards and related equipment, electronic components and systems, chemicals, metals, etc.*

GEOPHYSICS CORPORATION OF AMERICA, Bedford, Massachusetts, *performs research and development in the physics of the earth's atmosphere, and space and planetary environments and applies its findings to problems relating directly to national scientific and engineering goals. It also manufactures precision instruments and process equipment. The company conducts theoretical, laboratory, and field measuring programs in space sciences, meteorology, atmospheric modifications, nuclear weapons effects, and ballistic missile defense. Its manufactures include such diverse items as high-altitude balloons, lens test benches, vacuum furnaces, etc. The company is made up of the Physics Research Division, David W. Mann Company, Vacuum Specialties, Inc., and Viron Division.*

GRUMMAN AIRCRAFT ENGINEERING CORPORATION, Bethpage, New York, *is a primary manufacturer of military and commercial aircraft with research, design, development, and manufacturing experience in diversified fields such as VTOL aircraft, hydrofoil ships, missiles, and satellites. Currently, Grumman is working under contract with NASA for design and development of an Orbiting Astronomical Observatory. This vehicle is a precisely stabilized satellite which can perform a variety of astronomical experiments.*

W. AND L. E. GURLEY, Troy, New York, *has manufactured engineering, surveying, and scientific instruments since its founding in 1845, and has maintained its own design and lens making facilities for three-quarters of a century. It supplies both optical instruments of standard manufacture and special optical systems designed and produced to specification. Gurley is pre-eminent in the field of high accuracy linear and circular scales on glass in combination with optical coincidence reading systems, and also specializes in precision resolution targets and reticles for optical and photoelectric instruments made by mechanical, photographic, electroforming and electroetching methods.*

WAGN H. HARGBOL PRECISION OPTICS LABORATORY, 5 Forest Street, Arlington, Massachusetts

THE HARSHAW CHEMICAL COMPANY, 1945 East 97th Street, Cleveland 6, Ohio, *manufactures chemicals and chemical products primarily for industrial use. The Synthetic Crystal Division started operations with the introduction of optical quality lithium fluoride, and, in 1938, the first large optically clear rock salt crystals were produced. These operations have expanded to a complete line of alkali and alkaline earth halides of optical quality. For detecting radiation, Harshaw manufactures scintillation crystals, primarily thallium activated sodium iodide, but other combinations are also available including the organic type crystals. Special crystals for solar generators, silver chloride fibers, and maser crystals are also made.*

HILGER AND WATTS, INC., 431 South Dearborn Street, Chicago 5, Illinois, *was organized in 1959 by Hilger and Watts Ltd., London, makers of scientific instruments, jointly with Engis Equipment Company of Chicago, representatives of the English company for nearly twenty years, to maintain technical liaison, engineering information for the Hilger and Watts customers in the United States, facilities for research training, and continuing studies of future needs in the field of scientific instrumentation. Personnel and consultants are available for steadily increasing coverage in the field of vacuum spectroscopy, interferometry, x-ray, engineering optics, and precision technical instrumentation.*

HYCON MANUFACTURING COMPANY, 700 Royal Oaks Drive, Monrovia, California, *is a supplier to the aerospace industry and the government in the fields of aerial reconnaissance systems, automatic missile test equipment, and special communications and electronics systems. The Company supplies automatic checkout equipment to the U.S. Navy for advanced Tartar and Terrier families of missiles. Hycon has also designed and built a series of automatic radio locator beacons and produced a number of microwave components and associated equipment.*

INSTITUT DE L'ENERGIE SOLAIRE DE L'UNIVERSITE D'ALGEP, 2 rue Michelet, Algiers, Algeria, *is an institute in which one of the earth's natural energy resources is studied. Set in the heart of the Mediterranean basin, on the edge of the desert, the University of Algiers is peculiarly suited to study the development of solar energy. Created in 1959, the Institute's ten research sections cover physical studies in harnessing, transforming, heating, and electricity; synthetic chemistry; high-temperature mineral preparation; biological applications; etc.*

INSTRUMENT DEVELOPMENT LABORATORIES, INC., 67 Mechanic Street, Attleboro, Massachusetts, *has evolved from a research activity into a production facility. IDL photoelectric instruments for color measurement and control are industrial standards and illustrate IDL engineering ability to combine the best in optics, electronics, and mechanical design to solve a problem in measurement bettering the human eye. An example of these applied principles and techniques is the development of automatic temperature measuring and control equipment through the use of photoelectric optical pyrometry.*

INTERNATIONAL BUSINESS MACHINES CORPORATION, Thomas J. Watson Research Center, P. O. Box 218, Yorktown Heights, New York. *Areas of optics technology under investigation include injection gallium arsenide lasers, calcium fluoride masers, fiber optics, and fiber optics lasers; image and print scanning, display, and photo-forming systems; high-resolution photography, lens evaluation, photosensitive materials, and component evaluation for optical data processors. A photomemory which stores 60 million bits in ten square inches (64.5 sq. cm) of film emulsion was built by IBM Research for language translation under contract with the Air Force.*

ITEK CORPORATION, 223 Crescent Street, Waltham, Massachusetts. *Research activities in optics (one of several scientific disciplines which apply to Itek's field of specialization, information technology) are concentrated in the areas of theoretical optics, optical design, image evaluation, and precision measurement by optical means. These activities lead to a broad capability strong in every phase of the development of either a high-acuity reconnaissance objective or a specialized optical component tailored to handle specific information.*

KEUFFEL AND ESSER COMPANY, Hoboken, New Jersey. *The Optics and Metrology Division was created to specialize in the development and manufacture of optical-mechanical-electronic systems and components, especially for precise measurement and angles. In standard products, this Division maintains a complete line of optical alignment equipment, and, in defense applications, is engaged in the design and manufacture of special equipment on a contract basis.*

KINNEY VACUUM DIVISION, THE NEW YORK AIR BRAKE COMPANY, 1325 Admiral Wilson Boulevard, Camden 11, New Jersey, *manufactures high-vacuum evaporation equipment, an accessory line for thin film deposition and monitoring, large and small space environmental equipment, and complete high-vacuum pumping systems. A separate department is maintained and staffed for all phases of thin film deposition with production facilities including coating chambers up to 9 ft (3.75 m) diam, and a research and development staff to undertake any thin film problem.*

KOLLMORGEN OPTICAL CORPORATION, Northampton, Massachusetts, *specializes in the design, development, and manufacture of optical, electronic, and electromechanical instruments for remote viewing, testing, inspection, and measurement. Products vary in size from small borescopes to submarine periscopes; in types from nuclear and missile viewing systems through precision camera lenses and alignment telescopes, to a variety of sophisticated electro-optical instrumentation. Three wholly owned subsidiary companies contribute quantitative photoelectric equipment, high-resolution torque motors, tachometer generators, rotary and solid-state amplifiers.*

KOLLSMAN INSTRUMENT CORPORATION, Elmhurst, New York, *manufactures instruments, controls, and automatic celestial navigation systems for aircraft, missiles, and space vehicles. The Optical Department is located at Elmhurst, while at Syosset, L.I., Kollsman operates a modern production and assembly plant for astro trackers and allied ground support equipment. At Munich, Germany, Kollsman Luftfahrt Instrumente, G.m.b.H., produces precision aviation instruments.*

LIBERTY MIRROR DIVISION, LIBBEY-OWENS-FORD GLASS COMPANY, 811 Madison Avenue, Toledo 2, Ohio, *manufactures vacuum deposited coatings and precision optics including front surface mirrors; transparent mirrors; and coatings as follows: high-efficiency beam splitter, dichroic, ultraviolet, infrared, low-reflection, antistatic, and electrically conducting. These vacuum deposited coatings can be applied to all types of glass, plastics, epoxy material, and highly polished metals.*

LINK DIVISION/GENERAL PRECISION, INC., Binghamton, New York, *is the originator of flight simulator training equipment and a commercial manufacturer of automatic interferometric measuring instruments. Examples are the FRINGECOUNT Micrometer for measuring length, the GONIMET for measuring angles, and the Automated High Accuracy Coordinate Measuring Equipment for photogrammetric coordinate measurements.*

THE MICROCARD READER CORPORATION, West Salem, Wisconsin, *manufactures the hardware for use with microcards and related microforms used for storage and retrieval of information. This includes projection and direct-viewing types of reading equipment, machines for providing full-size copies directly from microcards, special step-and-repeat cameras, etc. As with all microforms, optical enlargement is required for reading and for the making of copies.*

NORTRONICS DIVISION OF NORTHROP CORPORATION, 500 East Orangethorpe Avenue, Anaheim, California, *was established to handle Northrop's growing activities in the development and manufacture of military optical, electronics, and mechanical systems and components. Nortronics now has four departments, one of which, Systems Support, is the center of optical research, engineering, and manufacturing; other departments also have optical groups active in their own specialized fields. The areas of Nortronics optical interests include: fire control instruments, special cameras, infrared systems, electro-optical devices, navigational systems, projection viewers, and other reconnaissance and photogrammetric instruments.*

OPTICS TECHNOLOGY, INC., 248 Harbor Boulevard, Belmont, California, *is engaged in contract research, systems development, and manufacturing. Research talent is active in the area of fiber optics and nonclassical optics. Systems work includes both components development and systems analysis and design. Manufacturing includes the production of thin film interference filters, fiber optics devices, and analytical and process control instrumentation.*

N.V. OPTISCHE INDUSTRIE "DE OUDE DELFT," Oude Delft 36, Delft, Holland, *founded in 1939, are makers of high-precision optical and electronic instruments, all of their own design, e.g., the Bouwers' concentric mirror system; a special night camera for filming scenes exclusively illuminated by moonlight; etc. Production plants are located in Delft and Leeuwarden in the Netherlands. Marketing and sales are organized on an international level, backed by a central staff in Delft with technically trained world-traveling delegates. The "Old Delft" has subsidiaries in the U.S.A., France, Germany, Italy, and the Netherlands.*

OPTOVAC, INC., East Brookfield Road, North Brookfield, Massachusetts, *specializes in the production of optical crystals grown from the melt, with particular emphasis on high quality optical calcium fluoride (fluorite), but also of sodium chloride, potassium bromide, potassium chloride, and other inorganic crystals. The company also is producing high quality optical maser crystals.*

OWENS-ILLINOIS, 1700 N. Westwood, Toledo, Ohio, *manufactures many products made from plastics, paper, and glass. The Technical Center at Toledo houses most of the Company's technical effort, which includes fundamental research broadly related to the fields of polymers and plastics, paper forest products, and glass and silicate chemistry, in addition to applied research, development, and engineering related to specific products.*

PACIFIC UNIVERSAL PRODUCTS CORPORATION, 168 Vista Avenue, Pasadena, California. *Facilities include metallic coatings, Schlieren wind tunnel mirrors, low reflection coatings, plate glass requirements to tight tolerances, magnesium fluoride coatings, gold coatings, camera lens coating and repairs, binocular lens coating and collimation, aluminizing and fabrication of telescope mirrors to 1/10 wave with protective silicon monoxide overcoating, etched or photo reticles and metal depositions of patterns on glass.*

PERKIN-ELMER CORPORATION, Norwalk, Connecticut, *was founded in 1937 as a source of precision optics and optical design in the United States. Since that time, the company has produced high performance optical systems, and has entered several new fields. It is actively engaged in the development of electronic-optical systems for space and defense programs, and is one of the leaders in the fields of laboratory and process control instrumentation. The company also produces a line of precision electronic components.*

PITTSBURGH PLATE GLASS COMPANY, Glass Research Center, Box 11472, Pittsburgh 38, Pennsylvania, *was founded in 1883 and today is a leading manufacturer of flat glass, chemicals, paints, brushes, and fiber glass. In 1914 the Company entered the optical glass field and since has been a supplier to the optical instrument and ophthalmic industries of an ever-broadening assortment of products. Pittsburgh Plate Glass Company makes optical, filter, and polished glasses for instrument makers and a complete line of glasses and pressings for ophthalmic lens manufacturers.*

POLAROID CORPORATION, Cambridge, Massachusetts, *is engaged in research, development, and manufacture of products involving the interaction of light and matter, with special emphasis on light polarizing filters and their applications, and on the cameras and films employing the one-step photographic process to produce finished pictures immediately after exposure.*

RAZDOW LABORATORIES INC., 377 5th St., Newark 7, N.J., *are devoted almost exclusively to the development and production of electro-optical measurement equipment for science, industry, and the military. As such, activities are carried on in the fields of optics, electronics, and allied areas of physics, and range from the theoretical analyses of given projects to their development, design, and final manufacture.*

RCA LABORATORIES, DAVID SARNOFF RESEARCH CENTER, Princeton, New Jersey, *built in 1942, is the headquarters and principal research facility of RCA Laboratories, and houses Materials, Electronic, Acoustical and Electromechanical, Systems, Computer, and Microwave Research Laboratories as well as several resident product division advanced development groups. Its function is to carry on basic and applied research relating to all principal areas of electronics, in order to provide the basis for development of new or improved products and services by the manufacturing and service divisions of RCA.*

SAWYER RESEARCH PRODUCTS, INC., 35400 Lakeland Boulevard, Eastlake, Ohio, *was founded in 1956 to produce commercial products by hydrothermal growth techniques, of which cultured quartz was the first. Licensed under Western Electric Company and Clevite Corporation patents, the Company drew mainly on results and experience in growing quartz gained in a research and development program that had been progressing continuously since 1945 at the Brush Development Company (later a division of Clevite) with financial support from the U.S. Signal Corps.*

SCIENTIFIC OPTICAL CORPORATION, 215 South Irwindale Avenue, Azusa, California, *produces high quality precision optics, creating components and devices for a multitude of industrial applications. CETRON, a leader in the field of electronic tubes and light control devices, recently merged its engineering capabilities with those of Scientific Optical.*

SEISCOR MANUFACTURING COMPANY, Post Office Box 1590, Tulsa 1, Oklahoma, *is a division of Seismograph Service Corporation and supplies the parent company with custom made optical pieces. Seiscor also offers a contract manufacturing service in electronic, electro-optical, and electromechanical equipment.*

SEMI-ELEMENTS, INC., Saxonburg Boulevard, Saxonburg, Pennsylvania, *is a producer of single crystals of various materials, ultra pure chemicals of an exotic nature, and rare earth materials. Over 750 different single crystals are available from stock for use in the laser and maser field, neutron diffraction plates, and Fermi surface work and studies. The company also produces complete laser and maser systems, and is currently carrying on research in the Iraser and Xraser fields.*

SIMPSON OPTICAL MANUFACTURING COMPANY, Chicago, Illinois, *serves the military, the machine tool, and the photographic industry, as well as marketing direct reading, high precision VERNAC measuring instruments. In addition to high precision lenses for optical tooling instruments, surveying equipment, television and motion picture cameras and projectors, Simpson produces reticles, employing the latest evaporation coating techniques. The Simpson engineering staff are experts in design of complete optical systems, and the Company maintains an optical laboratory in support of its research and development programs.*

SPACE TECHNOLOGY LABORATORIES, INC., Los Angeles 45, California, *as an industrial contractor to the Air Force, Army, NASA and other government agencies and industrial companies, performs research, development, engineering, fabrication, and testing in missile and space programs. STL employs more than 4000 persons, of whom more than 1700 are scientists and engineers, in the performance of over 80 current contracts and subcontracts. STL, through its Products Division, manufactures technical devices developed from its company-sponsored space technology research.*

THE TE COMPANY, 1221 Chapala Street, Santa Barbara, California, *is engaged in optical design and development, and in the production of custom optics. Industry and government are sponsoring Te work in areas including: optical payloads for satellite and space applications; missile and anti-missile sensing elements; battlefield optical aids; airborne reconnaissance and surveillance systems. Company facilities include a computer center, optical grinding and polishing shop, electronics laboratory, and precision optical assembly and test laboratory.*

TIFFEN OPTICAL COMPANY, 71 Jane Street, Roslyn Heights, New York, *manufactures photographic filters and optical accessories for industrial and scientific use. Tiffen has complete facilities for modern vacuum coating, an advanced color laboratory, and manufactures optical components from prototype to mass production. It specializes in grinding, edging, drilling, and polishing all types of glass. Tiffen has a modern metal working machine shop with multispindle automatics which go up to 10 cm diameter, as well as completely equipped tool rooms and secondary machines.*

TINSLEY LABORATORIES INC., 2448 6th Street, Berkeley 10, California, *was founded in 1926. It is engaged in the design and manufacture of precision optical components and optical instruments. These include missile and satellite components, special cameras, data acquisition equipment, tracking and astronomical telescopes.*

TROPEL, INC., 52 West Avenue, Fairport, New York, *is concerned with optical engineering and consulting. Activities are divided between the production of advanced optical designs, together with the development of computing methods, and the manufacture of special instrumentation including prototypes. Commercial instruments manufactured are vacuum ultraviolet monochromators and accessories, high-time resolution spectrographs, and UniSlide instrument slide units.*

UNITED LENS COMPANY, Southbridge, Massachusetts

VALPEY CRYSTAL CORPORATION, 1244 Highland Street, Holliston, Massachusetts, *formed in 1931, fabricate crystalline and glass materials for the optical and radio-electronics fields. A wide range of services is available to meet the growing needs of the precision optics and special fabrications industries, and specially trained optical engineers and technicians, utilizing modern equipment, are available for all research, development, and production needs.*

VAN KEUREN COMPANY, 176 Waltham Street, Watertown, Massachusetts. *H. L. Van Keuren pioneered the use of monochromatic light with optical flats for testing flatness and parallelism, and he designed a unique micrometer using lightwaves which permitted all operators to use the same pressure. Modern grinding, lappings, and polishing skills allow production of precision pivots, seals, rings, and other custom work as well as catalog items which include a complete line of dimensional gauges.*

THE WARNER & SWASEY COMPANY, CONTROL INSTRUMENT DIVISION, 32-16 Downing Street, Flushing 54, New York, *has been active in research and development in infrared physics of hot gases, gas radiation pyrometry, plasma spectroscopy, shock and detonation research, molecular physics, combustion spectroscopy, infrared instruments and techniques since 1946. In addition, the Division is active in the development of numerical control systems for automation. The organization now known as the Control Instrument Division of the Warner & Swasey Company has been in continuous operation, conducting research and development work in various fields, since 1936. Originally independent, the company was reorganized in 1954 and incorporated as The Warner & Swasey Research Corporation, in which a majority interest was held by The Warner & Swasey Company. In 1958 the research corporation was merged into the parent company under its present name, Control Instrument Division. The Division continues to operate its technical programs autonomously.*

WHITE DEVELOPMENT CORPORATION, 80 Lincoln Avenue, Stamford, Connecticut, *consulting physicists and instrument designers, is concerned with the design and development of optical instruments for the laboratory. Most of its products are manufactured by other instrument companies under license. The firm also designs and builds custom instruments and accessories.*

WOLLENSAK OPTICAL COMPANY, Rochester, New York, *has a complete line of 8- and 16-mm cine, TV professional 35-mm motion picture, still camera, wide-angle, telephoto, enlarging, portrait, and process lenses. Wollensak is the exclusive manufacturer in the U.S.A. of mirrotel lenses—lenses incorporating mirror optics, and in 1950 entered the field of high-speed photography with a line of FASTAX cameras. The third segment of Wollensak business is the design, development, and manufacture of precision optical-electro-mechanical devices.*

XEROX CORPORATION, 6 Haloid Street, Rochester 3, New York, *manufactures and markets office copying equipment and supplies, photocopy equipment and supplies, and photographic sensitized materials. It specializes in xerography, a unique dry electronic process for copy reproduction, which is featured in the company's desk size 914 Office Copier. Principal plants are in Rochester and Webster, New York.*

ZOOMAR, INCORPORATED, 55 Sea Cliff Avenue, Glen Cove, New York, *pioneered in varifocal optics and other high precision optics of original design. Its products include: Zoomar lenses; space optics for missiles and satellites; microscopic equipment; Zoomfinder for U.S. Signal Corps; optics for gun cameras; training devices for U.S. Navy.*

From the Editor

Let us interrupt the discussion of our correspondence to consider some matters of terminology in optics. In the June 1962 issue of *Physics Today* the report of the SUN (Symbols, Units, and Nomenclature) Commission of the IUPAP was presented in some detail. Many people who hastily read this concluded that the section on optics is now gospel and that their papers must conform to this new nomenclature. This is not quite true: the report was a provisional or preliminary set of recommendations, and it has not yet been adopted by the American Institute of Physics. This AIP adoption must in turn be preceded by approval of the Member Societies, and we of the Optical Society have a particular interest in the sections pertaining to optics. On certain matters which seem properly editorial your Editors have already acted without formal instruction from the Society; for example, all of the editors of the journals of the AIP or its Member Societies voted to accept the SUN Commission recommendation that units named in honor of scientists shall be represented by the name in lower case, but with its symbol or abbreviation capitalized. Thus the unit of inductance is the henry and its symbol is H, the unit of magnetic intensity is the oersted and its symbol Oe. In English a proper name has really arrived when we accept it into the language uncapitalized: braille, cereal, pasteurize, mesmerize, macadamize, vulcanize, diesel, saxophone. The expression of units derived from proper names

in lower case is not new, this has been AIP *Style Manual* etiquette for many years. What is new and perhaps controversial to us is the capitalization of the symbol. Some have asked why should joule and watt be so honored when erg and dyne are not? On some the spelling is even altered, such as decibel, dB and ohm, Ω. And what should we do about mho and daraf? The Swedes then argued that their letter Å is not the same as A, and comes in fact at the end of their alphabet (after z and before ä and ö). We have therefore agreed to reinsert the diacritical mark on the symbol Å, although the unit remains the angstrom. This is a slight variant from the SUN report, which recommended ångström for the unit.

At a meeting of the AIP Publications Board about a year ago the editors discussed this proposal to capitalize symbols of units which derive from proper names and decided to adopt this system as of July 1962. This is purely an editorial convention, already agreeable to most of the other member countries of the SUN Commission; the only objections were the minor quibbles mentioned above. On a more controversial matter, the use of the unit hertz, Hz, for cps, the AIP editors took exception. The present editorial policy of this journal is to accept hertz, Hz, if an author uses it consistently throughout, particularly in our foreign-language articles, but to prefer cps for English-language papers.

A few of our audience have grumbled at this change, but most of us have accepted the new convention philosophically in the interest of international uniformity. One of our authors was so anxious to change his angstroms from A to Å that he changed all his amperes as well.

Let us consider some of the other recommendations of the SUN report. The section which will surely stir up the most argument is section 7.6 (page 25 of the June 1962 *Physics Today*) where many of the symbols listed as "preferred" differ from those preferred for *Applied Optics* and *J. Opt. Soc. Am.* Dr. Judd has discussed our preferred units on the Editor's Page of *J. Opt. Soc. Am.* for April 1962. In a future column we will discuss some of the differences, and we hope that those of you who have opinions on nomenclature will express them to us prior to the vote for adoption of this section of the SUN Commission report.

Although the AIP Publications Board adopted the SUN table of prefixes to represent the various powers of ten, we have taken several exceptions to this. For example, 10^9 electron volts can be written as either GeV or BeV. The SUN report states that the use of double prefixes should be avoided when single prefixes are available. Thus nanometer, nm, is indicated as preferable to millimicron, mμ. We will continue, at least for the present, to accept millimicrons for the spectroscopic sense of wavelength of light, although nanometer is preferred for non-spectroscopic senses such as the thermal expansion of a rod or the displacement of an interferometer plate. (We do not wish to imply that we *encourage* the use of mμ; why not express the wavelength in angstroms?) Again, the use of μ to mean the noun "micron" is so widespread that we do not propose to limit μ to mean only the adjectival prefix "micro," so that 10^{-6} meter remains 1 μ and not 1 μm (micrometer). The SUN report gives "sr" as the symbol for steradian instead of the commonly used "ster."

Some readers were frightened by the British English used in the SUN report: metre, gramme, litre, dioptre. These spellings would of course be Americanized by the AIP. After this report is adopted, the AIP will issue a revised *Style Manual*. We will then expect prospective authors to conform to the approved nomenclature.

JOHN N. HOWARD

Books Received

Diffuse X-ray Reflections from Crystals, by W. A. Wooster. Clarendon Press-Oxford, New York, 1962.

Experimental Transition Probabilities for Spectral Lines of Seventy Elements, National Bureau of Standards Monograph #53, by Charles H. Corliss and William R. Bozman. Washington, D. C., 1962.

Japanese Journal of Applied Physics, eds. K. Kinosita and R. Ueda. Vol. 1, #1, July 1962.

Proceedings of the International Conference on Magnetism and Crystallography, September 1961, in 3 vols. Physical Society of Japan, March 1962.

Electroluminescence, by H. K. Henisch. Pergamon Press, Oxford, 1962.

Advances in X-ray Analysis, Vol. 5, ed. William M. Mueller. Plenum Press, New York, 1962.

Advances in Glass Technology. Plenum Press, New York, 1962.

Über den Einfluss der teildurchlässigen Schichten auf den Wirkungsgrad von Zweistrahlinterferometern, by Joachim Rienitz. Akademie-Verlag, Berlin, 1961.

The Mechanism of Glass Polishing: A History and Bibliography, by D .C. Cornish. BSIRA Research Report #R267. Taylor and Francis, London, 1961.

Transactions of the P. N. Lebedev Physics Institute, Vol. XV; Part 1—*Calculation of Wave Functions and Oscillator Strengths of Complex Atoms,* by L. A. Vainshtein; Part 2—*On the Broadening and Shift of Spectra Lines in the Plasma of a Gaseous Discharge,* by M. A. Mazing; Part 3—*On Spectral Excitation in a Spark Discharge,* by N. K. Sukhodrev; Part 4—*The Radioluminescence Yield of Organic Substances,* by Z. A. Chizhikova. Consultants Bureau, New York, 1962.

Molecular Spectroscopy. Butterworths, London, 1962.

Studies in Optics, by A. A. Michelson. Phoenix Science Series, U. of Chicago Press, Chicago, 1962.

Fifty Years of X-ray Diffraction, by P. P. Ewald. N.V.A. Oosthoek's Uitgeversmaatschappij, Utrecht, 1962.

Photographic Instrumentation, by Kenneth Shaftan and Dean Hawley. Soc. Photog. Instrum. Engrs., Redondo Beach, 1962.

Spectroscopy, ed. M. J. Wells. Inst. of Petroleum, London, 1962.

Unter der Leitung, von P. Gorlich. Neue Ergebnisse Molekulspektroskopischer, Untersuchungen, 1962.

Tables of Einstein Functions: Vibrational Contributions to the Thermodynamic Functions, by Joseph Hilsenrath and Guy G. Ziegler, NBS Monograph, Washington, D.C., 1962.

Bibliography of Atomic Transition Probabilities, by B. M. Glennon and W. L. Wiese. NBS Monograph, Washington, 1962.

Electronic Computers, Fundamentals of Theory, Design, and Application, by V. Zimin. State Publishing House, USSR Academy of Science., Moscow, 1962.

Science and Civilization in China, by Joseph Needham. Vol. IV, Part I, Physics. Cambridge U. Press, Cambridge, 1962.

Developments in Applied Spectroscopy, ed. W. D. Ashby. Vol. I. Plenum Press, New York, 1962.

HAVE YOU SENT IN THE $50 DEPOSIT FOR THE OSA GROUP FLIGHT TO EUROPE—see page 180

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The Optical Society of America was organized in 1916 **"to increase and diffuse the knowledge of optics in all its branches, pure and applied, to promote the mutual interests of investigators of optical problems, of designers, manufacturers and users of optical instruments and apparatus of all kinds and to encourage cooperation among them."** The Society invites to membership all who are interested in any branch of optics, either in research, in instruction, in optical or illuminating engineering, in the manufacture and distribution of optical goods of all kinds, or in physiological and medical optics. Further information may be obtained from the Executive Secretary of the Society. **Annual Dues:** Regular members and Fellows, $17.00; Associate members, $13.00; Corporate members, $125.00. These dues include subscription to the Society's official journal, the **Journal of the Optical Society of America,** but not to its other publications.

Meetings Calendar

1963

February

—	1st Australian Conf. on Electrochemistry, Sydney and Hobart *F. Gutmann, U. of New South Wales, P.O. Box 1, Kensington, N.S.W., Australia*
4–8	44th Norelco X-ray Analytical School, Henry Hudson Hotel, NYC *V. W. Palen, Philips Electronic Instruments, 750 S. Fulton Ave., Mt. Vernon, N.Y.*
5	SAS New York Sect., Hotel Manhattan, NYC
11–15	3rd Quantum Electronics Conf., Paris *Mme. Cauchy, 7 rue de Madrid, Paris 8, France*
20	OSA Natl. Capital Sect., Goddard Space Flight Center *H. K. Hammond III, Rm. 316, East Bldg., NBS, Washington 25, D.C.*
20–22	Internatl. Solid-State Circuits Conf., 10th ann., U. of Pa. and Sheraton Hotel, Philadelphia *S. K. Ghandi, Philco Scientific Lab, Blue Bell, Pa.*
28–Mar. 2	APS, Houston, Tex. *K. K. Darrow, 538 W. 120 St., New York 27, N.Y.*
28–Mar. 2	4th Omnibus Conf. on Experimental Aspects of NMR Spectroscopy, Mellon Inst., Pittsburgh, Pa.

March

4–8	14th Pittsburgh Conf. on Analytical Chemistry and Applied Spectroscopy, Penn-Sheraton Hotel, Pittsburgh *Box 1353, Pittsburgh 30, Pa.*
11–12	Inter-Soc. Color Council, Statler-Hilton Hotel, NYC *R. M. Evans, Eastman Kodak Co., Rochester 4, N.Y.*
20–22	Quantitative Spectroscopy at Elevated Temperatures and Selected Applications in Space Science Symp. (sponsored by Caltech, JPL, ARPA, IDA, AFOSR, AFCRL, and ONR) Pasadena *A. R. Laufer, ONR Pasadena, 1030 E. Green St., Pasadena, Calif.*
24–29	Am. Soc. of Photogrammetry, Am. Cong. on Surveying and Mapping, Washington, D.C.
25–27	**Optical Society of America Spring Meeting,** Jacksonville, Fla. *M. E. Warga, OSA, 1155 16th St. N.W., Washington 6, D.C.*
25–28	APS, St. Louis, Mo. *K. K. Darrow, 538 W. 120 St., New York 27, N.Y.*
27–29	Internatl. Symp. on Photochemistry, Rochester, N.Y. *AFOSR, Attn: Lt. Col. W. H. Wyatt, SRC, Washington 25, D.C.*
31–April 5	ACS, 144th Natl. Mtg., Los Angeles, Calif. *ACS, 1155 16th St. N.W., Washington 6, D.C.*

April

2	SAS New York Sect., Hotel Manhattan, NYC
14–18	Electrochem. Soc., Pittsburgh, Pa. *I. E. Campbell, Natl. Steel Corp., Weirton, W. Va.*
14–18	Electrochem. Soc. 1963 Symp. on Optical Masers, Penn Sheraton Hotel, Pittsburgh *H. R. Lewis, RCA Labs, Princeton, N.J.*
16–17	1963 Ohio Valley Instrument-Automation-Electronics Exhibition and Symp., Cincinnati Gardens *J. R. Douglass, 8603 Zenith Court, Brentwood, Cincinnati, Ohio*
16–18	Optical Masers—Polytechnic Internatl. Symp., NYC *L. Bergstein, Polytechnic Inst. of B'klyn, 333 Jay St., B'klyn, N.Y.*
18–20	APS N.Y. State Sect. Symp. on Biophysics, Union Col. and GE Co., Schenectady *Mrs. F. L. Gill, Physics, Union Col., Schenectady, 8, N.Y.*
22–25	APS, Wash., D.C. *K. K. Darrow, 538 W. 120 St., New York 27, N.Y.*
22–26	SMPTE, 93rd Semiann. Conv., Atlantic City, N.J. *SMPTE, 55 W. 42 St., New York 36, N.Y.*
23–25	Conf. on Electronic Processes in Dielectric Liquids, London *Inst. of Physics and Physical Society, 47 Belgrave Sq., London, SW 1, England*
29–May 3	SPSE Annual Conf., Ambassador Hotel, Atlantic City, N.J. *D. L. Castellini, 98 Leland Terrace, New Shrewsbury, N.J.*

May

—	2nd Hungarian Optical Conf., Budapest *Soc. of Optics, Acoustics and Film Technics, Szabadság-tér 17, Budapest 5, Hungary*
6–11	14th Natl. Science Fair-Internatl., Albuquerque, N.M. *Science Service, 1719 N St., N.W., Washington 6, D.C.*
2nd week	French Soc. of Ophthalmology, 70th Cong., Paris *M.-A. Dollfus, Soc. Française d'Ophtalmologie, 27, rue du Faubourg-St.-Jacques, Paris 16, France*
14	SAS New York and Delaware Valley Sects., Forrestal Res. Center, Princeton U., Princeton, N.J.
16–17	Soc. of Technical Writers and Publishers, 10th Ann. Conv., Boston, Mass.
20–23	14th Ann. Mid-America Spectroscopy Symp., Sheraton-Chicago Hotel, Chicago *J. E. Forrette, Borg-Warner Corp., Wolf and Algonquin Rds., Des Plaines, Ill.*
21–23	Am. Federation of Information Processing Societies, Spring Joint Computer Conf., Detroit, Mich.
22	OSA Natl. Capital Sect. *H. K. Hammond III, Rm. 316, East Bldg., NBS, Washington 25, D.C.*

June

—	APS, summer mtg., Buffalo, N.Y. *K. K. Darrow, 538 W. 120 St., New York 27, N.Y.*
—	Internatl. Comm. on Illumination, 15th Cong., Vienna, Austria
4–8	Soc. of Phys. Chem., ann. mtg., Paris *G. Emschwiller, Soc. de Chimie Physique, 10, rue Vauquelin, Paris 5, France*
6–8	Chem. Inst. of Canada, 46th Natl. Conf., Toronto, Ont. *CIC, 48 Rideau St., Ottawa 2, Ont., Canada*
6–9	Canadian Assoc. of Physicists, Laval U., Quebec City *L. Katz, U. of Saskatchewan, Saskatoon, Canada*
10–14	Triple Commission on Spectroscopy, Columbus *H. H. Nielsen, Ohio State U., Columbus, Ohio*
10–14	Molecular Structure and Spectroscopy, 18th symp., Columbus *H. H. Nielsen, Ohio State U., 174 W. 18 Ave., Columbus 10, Ohio*
13–Aug. 9	Geometric Optics Summer Course, Indiana U. *R. W. Everson, Div. of Optometry, Indiana U., Bloomington, Ind.*
17–24	CIE, Hofburg Palace, Vienna, Austria
17–28	AFOSR Summer Scientific Seminar on Topics in Optics, Clouderoft, N.M. *AFOSR Seminar, P.O. Box 1053, Holloman AFB, N.M.*
23–28	ASTM Ann. Mtg., Chalfonte-Haddon Hall, Atlantic City, N.J. *ASTM, 1916 Race St., Philadelphia 3, Pa.*
24–26	APS, Buffalo *K. K. Darrow, 538 W. 120 St., New York 27, N.Y.*
24–26	Internatl. Astrophysics Symp., Liège *M. Migeotte, Inst. d'Astrophysique, Cointe-Sclessin, Belgium*
24–27	Groupement pour l'Avancement des Methodes Spectrographiques, 25th Cong., Paris *GAMS, 1 rue Gaston Boissier, Paris 15, France*
24–28	Gordon Conf. on Magnetic Resonance, Tilton School, Tilton, N.H.
25–29	Oil and Colour Chemists' Assoc., biennial conf., Scarborough, England

July

1–5	IUPAC Internatl. Symp. on Macromolecular Chem., Paris *Symp. Sec., Lab. de Chimie Physique, 11, rue Pierre Curie, Paris 5, France*
1–5	Gordon Conf. on Chemistry and Physics of Space, Tilton School, Tilton, N.H.
1–14	Applications of Quantum Mechanical Methods to the Study of Molecular Properties, Menton *R. Daudel, Centre de Mechanique Ondulatoire Appliquee, 23, rue du Maroc, Paris 19, France*
2–5	Internatl. Symp. on Free Radicals, 6th, Cambridge *A. B. Collear, U. of Cambridge, Lensfield Rd., Cambridge, England*
5–9	IUPAC Conf., London *Sec., IUPAC Conf., 47 Belgrave Sq., London, SW1, England*
8–13	Ionization Phenomena in Gases, Orsay *P. Hubert, CENFAR, B. P. No. 6, Fontenay-aux-Roses, Seine, France*
10–17	IUPAC Congress, London *Sec., IUPAC Congress, 47 Belgrave Sq., London, SW1, England*

Applied Optics — Of Optics and Opticists

This column is compiled partly from information sent by our Reporters in various centers of optics across the continent, but the Managing Editor welcomes news from any source

> Oh, how I wish I could shut up like
> a telescope! I think I could if
> only I knew how to begin. *Lewis Carroll**

Near-infrared spectral observations of the moon were obtained in recent series of balloon telescope experiments high over the Southwestern United States. Called project SKYTOP, a balloon-borne Cassegrain telescope was successfully launched September 12 from Artesia, New Mexico, reaching an altitude of about 262 km. The launching was conducted by a team from AFCRL. Carried along on the 385-kg payload, in addition to the 30.5-cm Cassegrain telescope, was an interferometer spectrometer to take spectra of both the moon and the planet Venus. Instrumentation was designed by Roger A. Van Tassel of AFCRL. Other information obtained on this initial flight concerned the amount of water vapor which was present in the thin atmosphere above the balloon gondola. The instrumented gondola is stabilized by a gyromechanism designed for AFCRL under contract by Tufts University. A third objective of the flight was to obtain information required to measure the amount of different gases in the upper atmosphere of Venus. An instrumentation failure prevented the telescope from orienting on the earth's "sister planet" for a sufficient length of time.

The world's largest **solar telescope,** located at Kitt Peak National Observatory near Tucson, Ariz., was named last year for Robert R. McMath, in memory of the man whose scientific dream it represents. The giant instrument, which has a focal length of 91.4 m, will form an image of the sun 86.4 cm in diameter. The late Dr. McMath was a professor of astronomy at the University of Michigan and former board chairman of the Association of Universities for Research in Astronomy, Inc., which operates the new national observatory for the National Science Foundation. The McMath solar telescope, located 64 km southwest of Tucson, will permit studies of the sun in greater detail than has ever been possible. It will form a solar image larger and more brilliant than attainable with any other instrument . . . . **Gordon Newkirk, Jr.,** of the Boulder High Altitude Observatory, will edit the December 1964 issue of this journal featuring **solar optics.**

Atoms made visible by new research tool. The field ion microscope now permits direct visual observation of the atomic structure of metal surfaces. Crystal imperfections such as vacancies, interstitials, and dislocations can also be seen. Comparison of two micrographs, taken before and after an irradiation event, will show the change in position of even a single atom. This new research tool was described by Erwin Müller *Penn State* during a Symposium on the Properties of Surfaces held at the American Society for Testing and Materials September Meeting. At present, according to Dr. Müller, who developed the instrument, field ion microscopy can be used only on the refractory metals, and specimens must be formed with extremely fine needle tips. Also, the use of a very high electric field in the instrument exerts a high mechanical stress on the specimen. The resolution of the field ion microscope is about 2.5 Å; the lattice constants of the refractory metals are in the range of about 3 to 5 Å. This is the only microscope technique powerful enough to show directly the individual atoms of surfaces in their crystallographic arrangement and with their crystal imperfections. Dr. Müller stated that the unique possibility of extending surface research to direct observation at the atomic level justifies further work with this promising basic research tool.

A proposed policy for the publication of force constants, normal coordinates, and similar calculations. The last couple of years has seen a considerable increase in the number of papers on force constants and normal coordinates determined by the Wilson **FG** matrix method. This reflects, in part, the increasing ease with which such calculations can be made on a digital computer, but also the recent revived interest in this subject. Many of these manuscripts contain extensive tabular matter which is expensive to set in type, and it seems appropriate at this time to inquire into how many of these tables are really necessary. John Overend *Minnesota* suggests that the guiding principle is taken as: "Any numbers which can be calculated within half an hour on a modern, high-speed digital computer from the results given in the paper and standard physical constants should not be reproduced unless they are necessary for the physical and chemical discussions in the text, or a subsequent paper, or unless they represent new and significant results which cannot be obtained by standard methods." To be more explicit, he lists the obviously essential data: (1) The molecular geometry used in calculating the **G** matrix—in general masses need not be reproduced. (2) The functional form of V. He suggests this is important as it defines unambiguously the force constants. (3) Any assumptions about the force constants. It is important to know which force constants are calculated, which are transferred from other molecules, and which are set at arbitrary values. (4) Numerical values of force constants and details of how they were determined. (5) The data used in the calculation of force constants and normal coordinates; e.g., vibrational frequencies, Coriolis coefficients, centrifugal stretching constants, etc. (6) Some indication of the detailed quality of the fit of the force constants to the spectroscopic data. Many other data are nonessential; for example, $\boldsymbol{L}$ matrices, potential-energy distributions, Cartesian displacement coordinates, etc., and may be recalculated quickly from the essential data listed above. The display of such data for their own sake should be discontinued. But, if such information is really pertinent to the discussion in the paper (and the discussion not included to justify display of extensive tables) then only such material as is absolutely necessary should be given journal space. In the past, many authors have calculated vibrational frequencies and thermodynamic functions for isotopic substances which have neither been synthesized nor studied. In some cases these results are important, but in general they are of little interest. As they are now quickly calculated, they should not be published unless of real significance or unless the author wishes to pursue them in an extension of the work.

* This column was intended for the January issue, but, as the choice was news notes or papers, we decided you would rather have papers. Therefore some of this news is not so hot any more. M/Ed.

R. H. Greenler has moved from Allis-Chalmers to the U. of Wisconsin-Milwaukee .... **Sam S. Impiombato** has left Barnes Engineering and is now with Advanced Technology Laboratories. He will be responsible for a Washington, D.C., office in the capacity of Staff Liaison Engineer .... **R. A. Smith** moved in October from the University of Sheffield to take up the position of professor of physics and director of the Institute of Material Studies at MIT .... **Wayne G. Norton** has been appointed vice president and general manager of Optical Gaging Products. Mr. Norton was awarded the OSA Adolph Lomb Medal in 1944 .... Another Lomb Medalist (1956), **W. R. J. Brown** has moved from Itek to be Director of Research for United-Carr Fastener .... A third Lomb Medalist to appear in this column this month is **David Grey,** 1948 Medalist, formerly with Polaroid and now at the MIT Lincoln Laboratory. Dr. Gray is President of the OSA New England Section .... **Paul Kisliuk** has been named head of the Quantum Electronics Department at Aerospace Corporation, El Segundo, California. The department is in the Electronics Research Laboratory of the firm's Laboratories Division.... **David L. Fridge** has joined Electro-Optical Systems, Inc., as a Senior Physicist in the Quantum Physics Division. He will be engaged in research and development in the field of laser components, devices, and systems. Prior to joining EOS, Fridge was vice president for component development at Optics Technology .... **Martin Rome** was recently appointed Manager of the Photoelectric Department at the EMR Princeton Division, replacing J. P. Causse, who left EMR to take a high position with the French Government .... Lear Siegler, Inc., Instrument Division of Ann Arbor, Michigan, recently announced the appointment of **Paul E. Weber** as manager of Infrared Systems. Mr. Weber has worked in the development of infrared instrumentation in this country for over a decade; prior to that time he was active in the physics and optics efforts of Germany ... **L. L. Marton,** Chief of International Relations at the National Bureau of Standards, will be a Visiting Professor at the University of Paris, Faculty of Sciences, for the academic year, 1962–1963. He will teach and conduct a research project in electron physics at the University as well as visit foreign laboratories and scientists. Dr. Marton has also been invited to give a number of lectures in England and on the continent throughout the year .... **Robert E. Bishop,** formerly of Packard-Bell, is now general manager for Spectrolab, North Hollywood, California .... **William Elliott** *Baird-Atomic* has now begun half-time consulting work and systems studies for Diffraction Limited .... **George Zissis** is on leave of absence from the University of Michigan Institute of Science and Technology to the Advanced Research Projects Agency Institute for Defense Analysis, Washington, D.C. He will continue his activities in infrared aspects of missile defense .... **Dick Powell** after several years' absence from the infrared oriented community returns to his former company, The Aerojet-General Corp., Avionics Division .... **Farrell B. Brown** recently joined the Department of Chemistry of the Texas A&M College as a postdoctoral fellow of The Robert A. Welch Foundation. Working in molecular structure and molecular spectroscopy, Dr. Brown will carry out original investigations and studies in far infrareds pectroscopy and nuclear magnetic resonance spectroscopy. Dr. Brown was formerly with the University of Tennessee where he recently received the Ph.D. in Physical Chemistry. His doctoral research there was under William H. Fletcher and involved, "The Infrared and Raman Spectra and Inversion Phenomenon of Cyanamide and Denterated Cyanamide." .... **Earle K. Plyler** temporarily moved in December from the National Bureau of Standards to Florida State University in Tallahassee, as Chairman of the Department of Physics. Dr. Plyler, a Director of the OSA, is now a relatively close neighbor of OSA President, Stanley S. Ballard, who holds a similar academic position at the University of Florida in Gainesville.

The Eighth National IRIS Meeting found itself sharing the Philadelphia Hotel with the Fifth International Mushroom Growers Association. One wag saw nothing unusual in this, reports R. K. McDonald; "After all, we both work in the dark."

Readers' attention is drawn to .... AEC Reports available from the Office of Technical Services, Washington 25, D.C.: *Design calculations for rotating-mirror cameras*, Sep. 1962, 16 pp., LA-2723; and *Pulsed ruby laser for plasma interferometry*, Sep. 1962, 26 pp., LAMS-2734, both price $0.50. More than 350 Swiss patents are digested in the third issue of *Abstracted Swiss Patents* published by OTS. Patents abstracted in this issue range from a buttonhole sewing device to a new type electric grill. Each abstract gives a brief description of the device or process, together with data on its class, application date, publication date, when the patent was granted, and the inventor and owner of the patent. Complete copies of the patents themselves can be obtained (in the original language only) from the Commissioner of Patents, U.S. Department of Commerce, Washington 25, D.C., at 30 cents per page. Since patents vary in number of pages, price quotations for individual patents will be furnished on request by the Commissioner of Patents. The third issue of *Abstracted Swiss Patents*, containing 175 pages, may be ordered from OTS, U.S. Department of Commerce, Washington 25, D.C., order No. 62-11028, price $3.

Patents. The detailed accomplishments of international science and technology are completely described in the patent literature. To make this complete wealth of information conveniently and economically available to the engineering, industrial, and scientific community, Rowman and Littlefield, Inc., in cooperation with the United States Patent Office, has embarked on the publication of *The National Catalog of Patents*. Publication of the first two units of the *Catalog*, covering ELECTRICAL and CHEMICAL patents, launches the project. Rowman and Littlefield, Inc., is capable of undertaking a project of this nature and scope, being the publisher of the *Library of Congress Catalogs*, listing and describing all printed books deposited in the Library of Congress from 1898 to date. In essence each unit of the *Patent Catalog* will consist of all the patents granted in their field from 1790 through 1961. All patents in each area of interest are grouped together by Classes and Subclasses as defined by the Patent Office. Patents granted in their respective fields are shown in the form of one major claim and one drawing as exemplified in the Official Gazette of the Patent Office. In addition, related patents whose primary listing is in other fields are shown in the form of cross references. Each unit of the Catalog contains its own Manual of Classification and Index. The ELECTRICAL unit is being edited by a board of specialists under the chairmanship of Leonard Solon, physicist and research scientist. The editorial board chairman of the CHEMICAL unit is Kalman Held, chemist and scientist. Design, production, and format will be on a level commensurate with the importance of the project. The paper used has a guaranteed life span of 300 years, the binding is pyroxylin-coated buckram over heavy boards and stamped in gold. The ELECTRICAL unit, which includes COMMUNICATIONS and RADIANT FNERGY, is estimated to run to sixty-five volumes of approximately 640 pages each. The CHEMICAL unit will consist of sixty volumes. Each volume is $9^1/_2$ x $12^1/_2$. Delivery of the first volumes of these units will begin this year with delivery completed by December 1963. The publication price of *The National Catalog of Patents* will be $17.50 per volume for the sixty-five volumes of the ELECTRICAL unit and for the sixty volumes of the CHEMICAL unit. To facilitate publication and to bring

out the most needed patents first, the *Catalog* is being published in six series. Series Six, covering the years 1951–1961, will be published first, with other series to follow. Beginning in February 1963 the publishers issue a supplement to each unit containing all patents granted in that field during the previous year. This will also include a listing of all changes in classification and any other pertinent information necessary to the continuing use of the *Catalog* at maximum effectiveness.

National Bureau of Standards news this month includes .... A new research group for laboratory collision processes has been organized within the Upper Atmosphere and Space Physics Division of the Boulder Laboratories, National Bureau of Standards. The group will use optical techniques, including spectroscopy, to obtain collision cross sections and distribution functions for various gases of importance to atmospheric processes. The group was organized by Lawrence R. Megill of the Boulder Laboratories and now includes Eldon E. Ferguson, former member of the physics staff of the University of Texas, and Arthur L. Schmeltekopt and Frederick C. Fehsenfeld recent Ph.D. students from Texas .... To assist the International Committee on Weights and Measures in selecting secondary wavelength standards for interferometric measurement of length, the NBS has measured the vacuum wavelengths of most of the stronger lines of mercury 198 and of several easily resolved lines of krypton 86 relative to the international standard of length—the Kr^{86} line at 6057.80211 Å. The measurements were made using photographic interferometry. Selected wavelengths were then presented to the Committee for consideration .... The total number of calculated wavelength standards of neutral germanium in the vacuum ultraviolet region with uncertainties estimated to be within 0.0008 Å has been increased to about 100 lines as the result of a cooperative study by the NBS and Purdue University. Twelve additional standards from singly ionized germanium in this region were also calculated. This work, which was supported in part by the National Science Foundation, extended the interferometric region of measurement of neutral germanium lines (formerly 2019 to 4685 Å) to 12069 Å .... A viscosity standard sample of glass is now available from NBS for use in calibrating commercial glass viscosimeters. (Standard samples issued by NBS are described in Standard Materials, Miscellaneous Publications 241. This publication may be ordered for 30 cents from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C. Up-to-date supplementary inserts, which are issued periodically, are available upon request directly from NBS.) This homogeneous soda-lime-silica glass, NBS Standard Sample No. 710, will also be helpful in correlating interlaboratory test results of vitreous substances and in achieving improved quality control of glass products. Several glass research laboratories, participating in the effort, obtained viscosity data on specimens of the glass for Bureau analysis .... **Peter L. Bender** is among the first recipients of the newly established Samuel Wesley Stratton Award. The Awards are named for the first Director of the Bureau. In 1901 Dr. Stratton organized NBS as a unique scientific institution and, during a 21-year tenure of office, firmly established its position in the scientific and industrial community. He left NBS in 1922 to become the 9th president of MIT. Dr. Bender was honored for his contributions to precision electromagnetic measurement and, particularly, the determination of the gyromagnetic ratio of the proton .... NBS Technical Note 157, Dec. 1961 *Information Selection Systems Retrieving Replica Copies:* A State-of-the-Art Report by T. C. Bagg and M. E. Stevens, available from US Government Printing Office for $1.25. The report describes 15 systems employing search-type selection principles, and in addition discusses briefly microfilm aperture card systems and other devices used for address-location retrieval.

Foreign reports tell us that The Applied Physics Division of the National Research Council of Canada has moved to a spacious new building. The division, under L. E. Howlett, has three research groups active in optics, headed by K. M. Baird, P. D. Carman, and G. W. Wyszecki, respectively .... Britain has made contributions to the development of optical instruments for several hundred years. In the eighteenth century, for instance, John Hadley's sextant helped to revolutionize ocean navigation. Today, the British optical instrumentation industry, which comprises the manufacture of lenses, binoculars, microscopes, and all other optical equipment, continues to expand. Between 1958 and 1961 the value of deliveries increased from £5.7 million ($16.2 million) to over £7.6 million ($21.4 million) (including £2.5 million ($7 million) for export). Some of the most significant British developments in recent years have involved the application of electronics. One example, the *Rodolite,* is an optical measuring device which uses a circular defraction grating to obtain an optical straight line of great accuracy, and by using a transmission grating in conjunction with a mercury pool it is possible to define a line which is both straight and vertical. Two large electron microscopes working at about a million volts are to be constructed at the Cavendish Laboratory and the National Physical Laboratory; they should enable biologists and metallurgists to study much thicker specimens. Individual companies spend large sums on research and development and the scientific instrument industry has a joint research organization: the British Scientific Instrument Research Association with laboratories at Bromley, Kent. The Research Association investigates new technologies, conducts applied research, gives technical assistance to member firms, and maintains a general technical information service. In recent years it has become increasingly concerned with industrial instrumentation, and its main research projects involve thin films, detecting elements, glass phosphors, and optical receiving systems. The industry also benefits from research into electronics and machine tools carried out by research organizations not primarily concerned with instrumentation.

Optics Seminars. The U. of Utah, Salt Lake City, is holding a series of weekly optics seminars, with such topics as the following being discussed: Direct First Order Experiment on the Propagation of Light from a Moving Source; Simultaneous Measurement of Thickness and Index of Refraction of Thin Films by Methods of Ellipsometry; Optical Transfer Functions; Light and Information; Recent Advancements in Optical Filters; Diffraction from a Standpoint of Quantum Mechanics; Optical Spin-Pumping; and Transmission Characteristics of an Interface Separating an MHD Medium from an EM Medium. This journal would appreciate hearing about any other optics seminars that are in progress or projected.

Search for a "cat's eye" television camera tube able to supply a usable picture under conditions of very dim light has lead U. S. Air Force researchers to conclude that research must be directed toward the development of an electron amplifier for the tube itself. A report of this work has just been released to science and industry through the Office of Technical Services, U. S. Department of Commerce, viz. *Research on Optical Amplification Employing Electronic Scanning Techniques.* J. A. Hall and H. Sabanowitz, Westinghouse Electric Corporation, for the U. S. Air Force. December 1961. 275 pages. (Order AD 275 319 from OTS, U. S. Department of Commerce, Washington 25, D.C., price $4.)

Congratulations to .... **Frank Gerard Back,** widely known for his work on the zoom lens, awarded the 1962 Progress Award of the SMPTE .... **Emil Wolf** *Rochester* and **Leonard Mandel** *Imperial College* awarded the OSA Prize for the Best Paper presented to a meeting of the Society and subsequently published in *J. Opt. Soc. Am.* during 1961; their research was concerned with some of the basic properties of coherent light .... **James G. Baker** *Harvard* awarded the Elliott Cresson Medal of the Franklin Institute, for his many contributions to the design of optical instruments, particularly for his innovations in the design of astronomical tools and for his contributions to the design of cameras for satellite tracking and aerial mapping. Dr. Baker is the feature editor for this journal's January and February issues on astronomical instrumentation .... **Stanley D. Stookey** *Corning* awarded a Wetherill Medal by the Franklin Institute for his researches on methods of preparation of the Pyroceram glass-ceramics that have found diversified industrial and technological applications, including those in space application. The Franklin Institute is known among scientists not only for its awards but for its technical *Journal*, research laboratories, computing center, library, science museum, and education services, and its planetarium. The Institute, founded 138 years ago, was named in honor of Benjamin Franklin .... **Kenneth W. Ogle,** *Mayo*, awarded the Proctor Medal of the Association for Research in Ophthalmology .... **Mary E. Warga,** *Executive Secretary OSA*, who received the annual medal of the New York Section of the Society for Applied Spectroscopy, for her outstanding contributions to the field of spectroscopy .... and to **William F. Meggers,** recipient of the Pittsburgh Spectroscopy Award for 1963.

News from **SPSE** includes their election to membership of the following OSA members: J. Kent Bowker, Steve R. Colletti, Bernard Erde, Jack D. Frank, James E. Gillis, Jr., Donald J. Howe, H. Rudolph Inhelder, Erwin Jaffe, Kurt W. Jenkner, M. M. Rao, Gilbert H. Reiling, Frederick A. Schwertz, John V. Sharp, James E. Tudor, and Lynn L. Van Orden.

Maser news this month includes .... the publication in December of **OPTICAL MASERS,** a $5.00 Supplement to this journal. Concepts basic to the understanding of optical masers are discussed in a 15,000-word paper by **O. S. Heavens** *Royal Holloway College*, which in addition reviews the progress of this new field. Work on solid-state systems is summarized, and applications in the areas of fundamental experiments, communications, instrumentation, and surgery discussed. Gas systems including new results are dealt with in a comprehensive review by **W. R. Bennett, Jr.** *Yale*, also about 15,000 words. Selected papers from the publications of the Optical Society of America and of other societies are reprinted in this comprehensive volume and suggestions for further reading are given. The editorial is written by **Charles H. Townes** *MIT*. This valuable reference volume will not be sent automatically to all *Applied Optics* subscribers, so if you want it remember to send in the reply paid order card you will find inserted opposite page A4 .... Franklin Institute Stuart Ballantine Medals (awarded for outstanding achievement in fields of communications which employ electromagnetic radiation) go to physicists working on optical masers: **Charles H. Townes** *MIT* and **Arthur L. Schawlow** *Stanford U.*, recognized for their concept of a completely practical solid-state, three-level maser operating in the optical region. **Theodore H. Maiman** *Korad Corporation*, for his development of the pulsed maser operating in the optical region of the electromagnetic spectrum which was the first time that monochromatic emission at optical frequencies had ever been produced. **Ali Javan** *MIT*, for his conception and development of the continuous optical maser which utilized neon and helium gases. (Drs. Schawlow and Javan worked on the lasers at the Bell Telephone Laboratories.) .... the Quantatron maser group has incorporated under the name of the **Korad Corporation,** with Theodore Maiman as president. Headquarters are in Santa Monica, Calif. .... **Perkin-Elmer/Spectra Physics** announce the commercial availability of a continuous-wave gas laser emitting in the visible spectral region at 6328 Å. This laser generates brilliant red light, and is in production. Delivery 30 days; model 110 $7900; model 112 $10,900 .... **Electro-Nuclear Laboratories,** Mountain View, Calif., offer a new nanosource that provides a mercury discharge with a rise and decay time of less than one nanosec. Pulse width is variable from 3 to 30 nanosec with a 60 cps rep rate .... A similar precision gas laser—their Model 150—is also announced by **Optics Technology, Inc.** Belmont, Calif. .... The simultaneous transmission of hundreds of thousands of telephone conversations through a 5-cm waveguide and accurate navigation of space vehicles are but two of the many exciting possible applications covered in a report on the field of stimulated emission devices. This report was written by ten graduates of the Harvard Graduate School of Business Administration who spent one year studying this new field. It is a compendium of articles and publications written about masers and lasers, and is documented with hundreds of interviews with the scientists and businessmen active in this field. The report includes an exploration of how these devices work, a description of more than sixty possible applications, and an evaluation of the potential for many of these applications. The report entitled **Masers/Lasers** endeavors to bridge the gap between a technical appreciation of these devices and an understanding of their potential applications. The report is available for $18.75 from Maser/Laser Associates, P.O. Box 6, Cambridge 40, Mass. .... **Electro-Optical Systems, Inc.** has received a contract to develop a high-intensity light pump for lasers for the Navigation and Guidance Laboratory at the Wright-Patterson Air Force Base, Ohio. The company's Quantum Physics Division will use a new concept in high-intensity light generation to build the improved unit. .... The following is a verbatim translation which appeared in the July 1962 issue of *Zhurnal izobretenii*, the official Soviet patent organ. (The source is Patent 148441 in the names of V. A. Fabrikant, M. M. Vudynskii, and F. A. Butayeva, *Zhurnal isobretenii* no. 13, 1962, 20): *A Method for the Amplification of Electromagnetic Radiation; A method of amplifying electromagnetic radiation based on media with a negative coefficient of absorption and distinguished by the application of a multiple passage of the signal through the amplifying medium in order to increase gain.* The Aerospace Division of the Library of Congress points out that, although the patent was published in 1962, it carries an official date of 18 June 1951. In this connection, it should be noted that the same authors were previously granted a patent covering the general principle of maser action for the entire electromagnetic spectrum. This patent was also published in *Zhurnal izobretenii* [no. 20, 1959, 29] and, as in the present case, was backdated to 18 June 1951. In the case of the present patent, which apparently describes the Fabry-Perot interferometer principle used in current optical and infrared masers, the 1951 date seems remarkably early. Moreover, Fabrikant has never indicated any application of the interferometer in his own gas laser experiments, nor has he been credited in the Soviet literature with its invention. The idea of using parallel-plate resonators for submillimeter, infrared, and optical wavelengths has generally been credited in the Soviet literature to A. M. Prokhorov, who first advanced it in 1958 and analyzed it theoretically in a number of papers .... A demonstration of the possibility of optical computing has been made by the IBM Deutschland Laboratories in Boblingen, Germany. A device prepared there uses light instead of electrical currents, to manipulate information. This idea has been under consideration in several countries, and interest has intensified with the advent of

the optical maser, which provides powerful and coherent beams of light, on to which information could be impressed, reports England's *New Scientist*.* The German device uses a conventional source of light and is not intended to be more than a demonstration. The beam of light is modulated in a very simple way, by polarization. Thus, if the light vibrations are in one plane it signifies "0" and, if in the plane at right angles, "1"—thus providing the binary code familiar to computer engineers. Computing is made possible by a suitable inverter element which can rotate the plane of polarization by 90° as the light passes through it. Two kinds of controlled inverters are possible in principle, mechanical and electrical, but only the latter is practicable. The input instructions are in electrical form, supplied to a row of inverters through which the light beam passes. The light is polarized as it enters the system; as it emerges it is confronted by another polarizer (or "analyzer"). If its plane of polarization is such that it can be transmitted through the analyzer it will produce a signal in a photocell at the end of its journey: if it is extinguished by the analyzer, it will not. Successful preliminary experiments have now been carried out with a four-figure addition system, which adds together two four-figure binary numbers using a nine-step program; the result is a five-figure binary number. In these experiments, the inverters were constructed from potassium dihydrogen phosphate crystals across which electric fields could be applied to produce the desired rotation. The limiting factor of such a system is the time taken to establish the high voltages required across the crystals; the actual switching of the light beam from one plane of polarization to another occurs instantaneously as the light passes through. Once the voltages have been set up, the computation takes only the time needed for the light to go from the source to the photocell. The inventor of this system of optical computing, Karl Ganzhorn of IBM Deutschland, has claimed three advantages for it: The electrical input is completely separated from the optical output of the system. A single optical inverter can deal simultaneously with numerous individual parallel light signals, which remain completely unaffected by each other. Finally, the system can handle up to nine successive program operations without the need for amplifying the lightbeam, whereas the normal electronic computer can deal only with two operations before amplification becomes necessary. The greatest disadvantage at present is the need to use high voltages, of the order of 1 kV, to produce a change of polarization in the phosphate crystals (a transistor typically works at 20 V) . . . . Two companies accomplishing continuous operation of a gallium-arsenide injection laser are **IBM Corporation,** New York, and **General Electric Company,** Schenectady, N.Y. This new† type of laser generates coherent light directly by passing an electric current through a semiconductor crystal.

Recent AFOSR grants include U. of New Mex., J. R. Foote, *1963 Summer Scientific Seminar on Topics in Optics*, $26,300.00; and Johns Hopkins U., D. W. Robinson, *High Resolution Studies in the Far Infrared*, $65,378.00.

* November 1962 issue.

† When this was written—M/Ed.

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OSA Corporation Members news . . . .Barnes Engineering Company, Stamford, Conn. (infrared and electro-optical instrumentation) has acquired the Versatronics Corporation, Fort Walton Beach, Fla. All Versatronics personnel have been retained. According to Eric M. Wormser, vice-president in charge of Barnes' defense and space activities, the purchase extends the company's capability to provide complete systems for missile range applications. Barnes has maintained an engineering office in Cocoa Beach (Fla.) for the past two years, providing support for Atlantic Missile Range activities. Plans are under way to combine the former Versatronics and Barnes Florida groups at a single location in the vicinity of Cape Canaveral. The resulting organization will be the Barnes Engineering Company Range Systems Division and will be under the direction of Harry W. Stulting, a vice-president of Barnes who is being transferred to Florida. This new division will expand Barnes' capabilities to include a new line of servo-controlled tracking pedestals, systems engineering, and complex systems integration. The scope of the work to be accomplished will embrace design, engineering, fabrication, and field support of electro-optical and electromechanical range equipment. . . .Acquisition of a new facility at Southampton Airport, England, for Kollsman Instrument Limited was announced recently. Kollsman Instrument Limited, operated by **Kollsman Instrument Corporation of New York**, moved into its new plant comprising 4182 sq m on November 1, 1962. The major production in this English subsidiary will be in the fields of celestial navigation and air data instrumentation for aircraft, similar to the principal fields of endeavor of Kollsman Instrument Corporation in the United States. . . . .A new series of ceramic photon counters, optical instruments which measure the intensity and variability of ultraviolet radiation in narrow bands of the solar spectrum, is offered by the **Geophysics Corporation of America** for inclusion in rocket and satellite space probes, or for use in laboratory research. The basic design for the small devices was developed at the NASA Goddard Space Flight Center. Aboard a rocket or satellite the instruments can be used to measure Lyman alpha radiation and other portions of the solar spectrum which do not penetrate to the earth's surface. In the laboratory, in conjunction with a light source able to simulate these wavelengths, the counters may be used to perform absorption studies of gases or to determine the reflectivity of metals. Measurements may be performed in such narrow spectrum bands as 1050–1180 Å, 1050–1250 Å, 1050–1350 Å, and 1225–1350 Å . . . . A NASA contract for the design and development of a spectrophotometer for astronomical research has been awarded to **Kollmorgen Corporation,** Northampton, Mass. The ultraviolet rocket spectrophotometer will be used by Goddard Space Flight Center, to measure the spectral properties of stars in light outside the earth's atmosphere . . . . A crucial problem in optical satellite tracking has been to devise means for making some of the precision photographic star atlases and catalogs available at the point of observation. To solve this problem **W. & L. E. Gurley,** Troy, N. Y., designed a rapid comparator with a read-out accuracy of $\pm 20\mu$, which could be used to measure distances from 0.1 mm to 300 mm in a matter of seconds. The comparator is used to make precise measurements on star charts and photographs.

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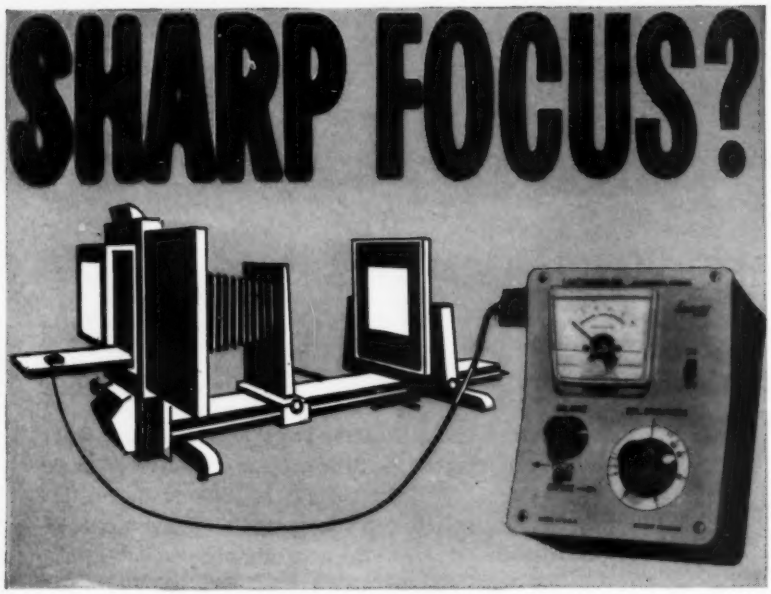

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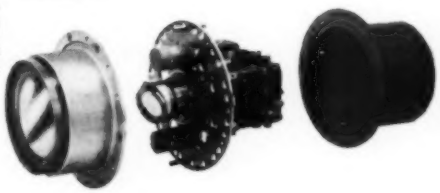

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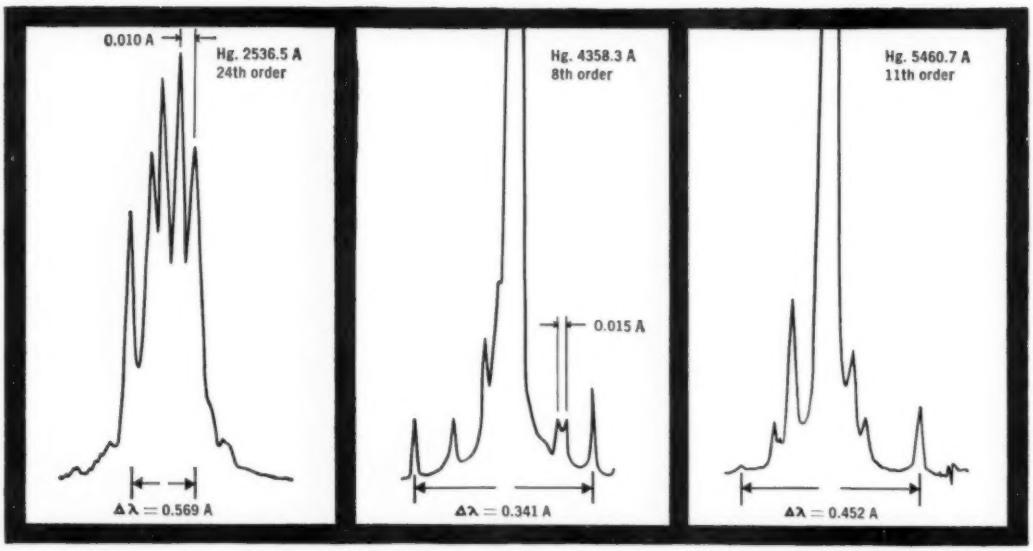

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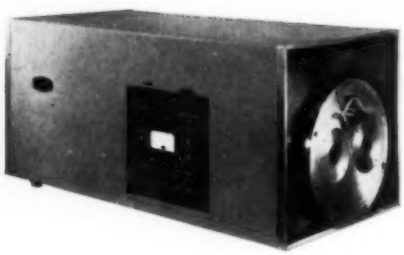

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